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The Impact of Design-Based Modeling Instruction on Seventh Graders' Spatial Abilities and Model-Based Argumentation

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**THE IMPACT OF DESIGN-BASED MODELING INSTRUCTION ON SEVENTH
GRADERS' SPATIAL ABILITIES AND MODEL-BASED ARGUMENTATION**

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ABSTRACT

THE IMPACT OF DESIGN-BASED MODELING INSTRUCTION ON SEVENTH GRADERS'
SPATIAL ABILITIES AND MODEL-BASED ARGUMENTATION

William J. McConnell
Old Dominion University, 2015
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Due to the call of current science education reform for the integration of engineering practices within science classrooms, design-based instruction is receiving much attention in science education literature. Although some aspect of modeling is often included in well-known design-based instructional methods, it is not always a primary focus. The purpose of this study was to better understand how design-based instruction with an emphasis on scientific modeling might impact students' spatial abilities and their model-based argumentation abilities. In the following mixed-method multiple case study, seven seventh grade students attending a secular private school in the Mid-Atlantic region of the United States underwent an instructional intervention involving design-based instruction, modeling and argumentation. Through the course of a lesson involving students in exploring the interrelatedness of the environment and an animal's form and function, students created and used multiple forms of expressed models to assist them in model-based scientific argument. Pre/post data were collected through the use of The Purdue Spatial Visualization Test: Rotation, the Mental Rotation Test and interviews. Other data included a spatial activities survey, student artifacts in the

form of models, notes, exit tickets, and video recordings of students throughout the intervention. Spatial abilities tests were analyzed using descriptive statistics while students' arguments were analyzed using the Instrument for the Analysis of Scientific Curricular Arguments and a behavior protocol. Models were analyzed using content analysis and interviews and all other data were coded and analyzed for emergent themes. Findings in the area of spatial abilities included increases in spatial reasoning for six out of seven participants, and an immense difference in the spatial challenges encountered by students when using CAD software instead of paper drawings to create models. Students perceived 3D printed models to better assist them in scientific argumentation over paper drawing models. In fact, when given a choice, students rarely used paper drawing to assist in argument. There was also a difference in model utility between the two different model types.

Participants explicitly used 3D printed models to complete gestural modeling, while participants rarely looked at 2D models when involved in gestural modeling. This study's findings added to current theory dealing with the varied spatial challenges involved in different modes of expressed models. This study found that depth, symmetry and the manipulation of perspectives are typically spatial challenges students will attend to using CAD while they will typically ignore them when drawing using paper and pencil. This study also revealed a major difference in model-based argument in a design-based instruction context as opposed to model-based argument in a typical science classroom context. In the context of design-based instruction, data revealed that design process is an important part of model-based argument. Due to the importance of design process in model-based

argumentation in this context, trusted methods of argument analysis, like the coding system of the IASCA, was found lacking in many respects. Limitations and recommendations for further research were also presented.

This work is dedicated to my family. Without the support of each and every one of them, I could not have completed this work. To my parents, whose unwavering belief and support provided me the confidence and persistence to follow through with my most important goals—you have been and will always be an inspiration. To my wife and children, who have sacrificed time and time again so that I may study, write and travel, yet all the while have provided a positive boon of support and encouragement. I am truly blessed to have such a loving and supportive family and I dedicate this and all the work that went with it to them.

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Chapter 1: Introduction

In traditional standards-based K-12 science classrooms, science and engineering practices are underemphasized while educators' primary instructional goal is to have their students gain science content knowledge (NRC, 2013). Unfortunately, traditional science instruction can present a disconnected, confusing, and somewhat less than meaningful view of science and engineering practices that hinders students from becoming scientifically literate; one of the main goals of science education (NRC, 2013). As defined in reform literature, science practices are a combination and a melding of both the skills and knowledge needed to engage meaningfully in scientific inquiry (NRC, 2012).

One document of contemporary reform already adopted in many US states is the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013). The NGSS incorporates engineering standards alongside science standards and stresses the importance of *doing* by establishing student learning standards as performance expectations (NGSS Lead States, 2013). This sweeping shift from content-based to performance-based standards presents a formidable challenge to today's educators. They must be able to develop and implement effective instructional methods that embed science and engineering skills and content into curriculum in a way that allows students to learn by doing.

The integration of engineering and science practices within science education reform has given much attention to instructional methods like Learning by Design (Kolodner et al., 1998) and Design-based Science (Fortus, Krajcik, Dersheimer, Marx, Mamlok-Naaman, 2004) that use engineering design challenges to integrate science,

technology, engineering and math (STEM). In both of these methods the development and use of two dimensional (2D) and/or three-dimensional (3D) models is an important component providing catalyst for student discussion and argument. Within the NGSS (2013) ‘developing and using models’ and ‘engaging in argument from evidence’ (NRC, 2012, p.42), are practices evident in several performance expectations across all age levels of the standards (NGSS Lead States, 2013). In current literature, design-based instruction often involves the construction of models using materials often used in classrooms in a hands-on fashion (eg. paper and pencil drawings, posters, wood, Legos, etc.), yet with the growing amount of user-friendly, cheaply-priced technology available for design, it seems that tools similar to those of professionals are attainable to any public school with an internet connection (Ratto & Ree, 2012).

Research involving students’ use of computer-aided design (CAD) software, which could be used to design models in science, has shown increases in students’ spatial performance (Toptas, Celik, & Karaca, 2012). Furthermore, studies have linked spatial abilities to performance in STEM subjects in school (Carter, LaRussa & Bodner, 1987; Lord, 1987; Pallrand & Seeber, 1984; Kali & Orion, 1996; Harris 1981), interest in STEM careers, and subsequent success in STEM careers. It is important to note that science education reform documents (eg. NGSS Lead States, 2013; AAAS, 2000) and science education research literature (eg. Dickerson, Penick, Dawkins & Van Sickle, 2007) do clearly acknowledge the need to provide students spatial learning opportunities throughout their K-12 schooling. Gilbert and Ireton (2003) stated, “Ideas and activities that involve modeling with computers should be a key part of the science curriculum” (p. 66). At this time design-based modeling using 3D printing technologies to create models

and its impact on students' spatial abilities have received little attention in K-12 science education research literature.

An integral component of modeling is argumentation; another valued and important component of science that suffers scant attention in K-12 schools. In most design-based and model-based methods of instruction, discussion and argument is an important structural component of the curriculum. For example, Wendell and Rogers (2013) demarcated language and the encouragement of scientific discourse as a major principal of Design-based Science. Gilbert and Boulter (2000) note the importance that students engage in model-based argument to constantly evaluate and improve models. On a similar note, in their review of Model-based Learning research, Loucha and Zacharia (2012) acknowledge discourse as an important component of the modeling process and one that is in need of more investigation.

Though there are varied approaches to design-based instruction, all focus on the design of an artifact as a primary goal (Fortus et al., 2004). Through the design and often the construction of these artifacts, students learn science concepts in various ways depending on the method of design-based instruction. Model-based instruction also incorporates student construction of artifacts, but there is less of a focus on the creative process of design, construction, and testing of the artifact and the focus is primarily on the appropriateness of the artifact to function as a scientific model. Though studies have found both design-based and model-based instructional methods to be effective in building science content knowledge (eg. Fortus et al., 2004; Barab, Hay, Barnett & Keating, 2000) there are no studies that document how design-based modeling instruction that incorporates the use of 3D printing technologies for modeling purposes might impact

students' spatial abilities or model-based argumentation. The increasing amount of practitioner articles in science education journals that involve 3D printing technologies is proof that many educators now have access to these technologies with students of various ages (eg. NSTA, 2013). It is crucial that researchers investigate how these technologies might fit into current science education reform in a way that benefits teachers and students alike.

The purpose of this study was to investigate the impact design-based modeling instruction had on the spatial abilities and model-based argumentation abilities of seventh grade students. In particular, the design-based instruction in this study involved students in iterative model design and construction in order to explain and argue their ideas. Before more explanation of the study, it is important to describe terms crucial to the study.

Design-based Instruction

In their review of the literature on several design-based methods that have shown promise in science education, Wendell and Rogers (2013) found several commonalities: 1) a design challenge is proposed to students 2) students work in groups to iteratively solve the design challenge by constructing a concrete artifact 3) Students engage in written or pictorial record keeping 4) teachers guide students to incorporate science ideas within their designs, and 5) students reflect of their design in class discussion. In this particular study, all aforementioned components were incorporated, but more specifically, the instruction most resembled design-based modeling, first proposed by Penner, Giles, Lehrer, and Schauble (1998). Design-based modeling involves the iterative

design of a scientific model where students attempt to represent their science ideas in representational forms.

Modeling

Modeling is the process of developing a representation of an object, event, process or system (Gilbert & Boulter, 1998; Zhang, Liu, & Krajcik, 2005). Within this particular study, modeling is the basis of students' design process, so that they are designing a representation of an object that will assist in their explanation and argument of a system.

Spatial Abilities

When analyzing the literature involving spatial abilities, it is evident that differing spatial abilities definitions exist. This study draws from the work of Linn and Peterson (1985) that demarcates three categories of spatial abilities. Spatial Perception is a category that deals with the ability to determine spatial relationships with respect to the orientation of one's own body, in spite of distracting information. Spatial Visualization involves the ability to manipulate complex spatial information when several stages are needed to produce the correct solution. Mental Rotation is a category that involves the ability to rotate, in imagination, quickly and accurately two- or three-dimensional figures.

In a meta-analysis by Maeda and Yoon (2013), mental rotation showed greater differences between individuals as opposed to other spatial abilities. Also, they note the similarities between this ability and tasks related to STEM performance in school as well as STEM careers (Maeda & Yoon, 2013). For these reasons, this study focused on mental rotation abilities so that it may provide

better understanding of case differences on this particular aspect of spatial abilities as a whole.

Scientific Argument and Scientific Curricular Argument

This study is informed by Van Eemeren and Grootendorst's (2004) definition of argumentation. "Argumentation is a verbal, social and rational activity aimed at convincing a reasonable critic of the acceptability of a standpoint by putting forward a constellation of propositions justifying or refuting the proposition expressed in the standpoint (2004, p. 1)." With this definition in mind, it is evident that scientific argument in K-12 classrooms is different than scientific argument in professional contexts. Mendonca and Justi (2014) proposed the term "scientific curricular arguments" (SCA) to differentiate between scientific argument in professional contexts and the overtly more simplistic arguments in K-12 learning environments. Though they are more simplistic, SCA can still involve claims, theoretical or empirically based justifications, and persuasion (Mendonca & Justi, 2014).

Specific 3D Printing Technology Description for the Current Study

In particular, this study defines 3D printing technology the tools needed to create a three dimensional product: computer aided design (CAD) software and a 3D printer. When professionals speak of 3D modeling, they often highlight the use of CAD software. Again, this results from a blending of terms. In essence, 3D modeling requires one to design a model, hence, I contend that creating a model, or a prototype, through the use of CAD software involves students in engineering design process skills. 3D printing technology therefore provides students with a unique blend of authentic engineering, technology, and scientific processes.

In this particular study, the 3D printing technologies involves both hardware and software. First, the students draw their design using browser-based CAD software called Tinkercad (Autodesk, 2015). This program is similar to engineering design software but is much more user-friendly and primarily for non-professional use. Tinkercad allows users to manipulate three dimensional figures in order to customize their own unique design and/or modify other designs in order to 3D print, download, or share designs with others (Autodesk, 2015).

MakerWare (MakerBot Industries, LLC, 2015) is a similar CAD program that is highly compatible to the 3D printer that was used for this project. The researcher imported the groups' Tinkercad (Autodesk, 2015). files to MakerWare (MakerBot Industries, LLC, 2015) in order to scale and edit groups' final designs to prepare them for printing. The 3D printer was a MakerBot Fabricator 2X (MakerBot Industries, LLC, 2015). It is able to print out three-dimensional models of just about anything one might draw as long as it can fit on the platform. In this lesson, students utilized only Tinkercad on their own. Though the students were able to view the printer printing, the researchers were the sole users of the 3D printer and MakerWare (MakerBot Industries, LLC, 2015) due to time constraints.

Theoretical Framework

The theoretical underpinnings of this study are situated in the basic premises of constructivism. Gilbert, Pietrocola, Zylbersztajn and Franco (2000) broadly define constructivism as "Using existing ideas to construct meaning from new experiences whilst using acquired experience for producing new ideas." In this sense, design-based instruction and student-generated models are valued educational approaches. They both

promote iterative processes that allow for collaborative experiences and amendments to initially proposed solutions. This study adopts the framework described by Justi and Gilbert (2002). They describe three facets of learning within science education: learning science, learning about science, and doing science. *Learning science* involves students learning about the “nature, scope and limitations of the main scientific or curricular models”; *Learning about science* involves students learning “to evaluate the role of models in the development and dissemination of the results of scientific research”; and *Doing science* involves student in learning “to elaborate, express, and test their own models (Mendonca and Justi, 2014, p. 194).” In this sense, students’ design, construction and use of models is of crucial importance in science education.

Theory developed across STEM educational research domains involving design-based instruction and modeling-based instruction assisted in the construction of the framework illustrated in Figure 1. Penner et al. (1997) first put forth design-based modeling as a type of design based instruction that seems to be a blend of both design-based and modeling-based instruction. A main component of this instruction the teacher has students build 2D and 3D models as a design challenge. The construction of 2D drawings, 3D drawings and 3D artifacts are spatial experiences that are known to increase spatial abilities of students (eg. Linn & Peterson, 1985; Hansen, Barnett, Makinster, & Keating, 2004). In science education, the importance of employing several models is thought to promote model-based transformational reasoning (Ramadas, 2009). Therefore, the construction of several modalities of models (eg. visual, verbal, gestural, and concrete) allows for model-based transformational reasoning. This type of reasoning is a negotiation among visual-spatial thinking and other types of reasoning among one or

more models. One might note that a double-sided arrow connects spatial experiences and model-based transformational reasoning in Figure 2. Not only does the spatial experience of constructing several models allow for model-based transformational reasoning, but the reasoning also allows for more spatial experiences. One aspect of this reasoning is the transformation from 2D to 3D representations. Several studies found that though it was important for science understanding, many students have great difficulty moving from 2D to 3D representations (eg. Freedman, Gellar, & Kaufmann, 2010). In order to facilitate this transformation, Eriksson, Linder, Airey, & Redfors (2014) found that in order for transformational reasoning to occur, students needed to encounter 3D models and representations from different viewpoints. Both spatial experiences and the model-based transformational reasoning as described have been found to build spatial abilities (Eriksson et al., 2014; Terlecki & Necombe, 2005; Tracy, 1987). As mentioned in the introduction, spatial abilities are linked to student performance in STEM.

Gilbert and Boulter (2000) often state the importance of discussion during modeling. Mendonca and Justi (2013) purport that the construction of several different models in a classroom allows and promotes argumentation. This line of reasoning also asserts that model-based transformational reasoning is related to model-based argumentation. In fact, students often need to merge several modes of representation in order to explain or present their ideas concerning their models (Subramaniam & Padalkar, 2009). Fortus et al. (2004) also found students' construction of visual or concrete models tends to promote a sense of ownership while Maia and Justi (2009) found that when students develop model-based arguments, it positively impacts their sense of ownership. Sense of ownership in general has been linked to increased science

interest among students (Oneill, 2005). Mendonca & Justi (2014) found that Model-based argumentation helped build a depth of science knowledge, and Falk, Storksdieck and Dierking (2007) posit that science interest is related to science knowledge gains. It is well known in science education research that the amount of science knowledge that a student has and the amount of interest a student has in science impact their science performance. Figure 1 illustrates many interrelated components of design-based modeling found in various studies.

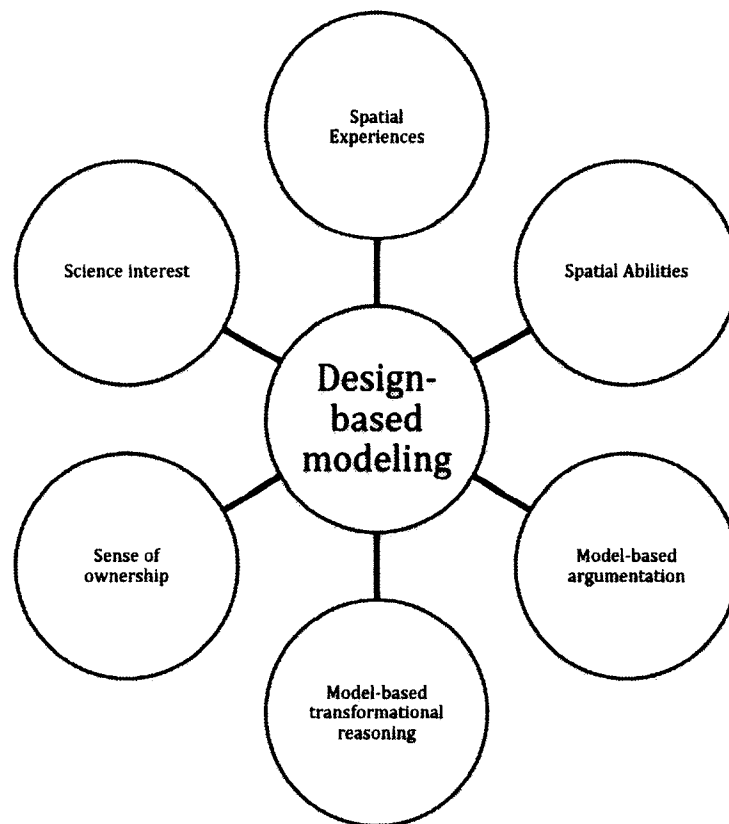


Figure 1. Interrelated components of design-based modeling.

Gilbert and Boulter (2000) often mention the inextricable link between models and argumentation. This study will attempt to investigate argumentation with the use of

models and will use the Model of Modeling Diagram (MMD) (Figure 2) as a framework to delineate four stages of modeling (Justi and Gilbert, 2002, p. 371). Stage one encompasses the production of a mental model using prior experiences and knowledge while simultaneously selecting a reality in their experiences to help to describe their mental model. Stage two involves the expression of the mental model in one or more representational forms (eg. visual, verbal, concrete). While articulating their thoughts in representational form, ones' model may change. In stage three, thought or empirical testing of the models occurs. These tests will vary depending on resources and time, but should assist in rejecting or accepting the model. Stage four corresponds to model evaluation. At this time one would assess the models' fit to its purpose as well as acknowledge components of the concept, phenomena or system that it does not explain. Note that testing of the model is different than evaluation of the model in the MMD.

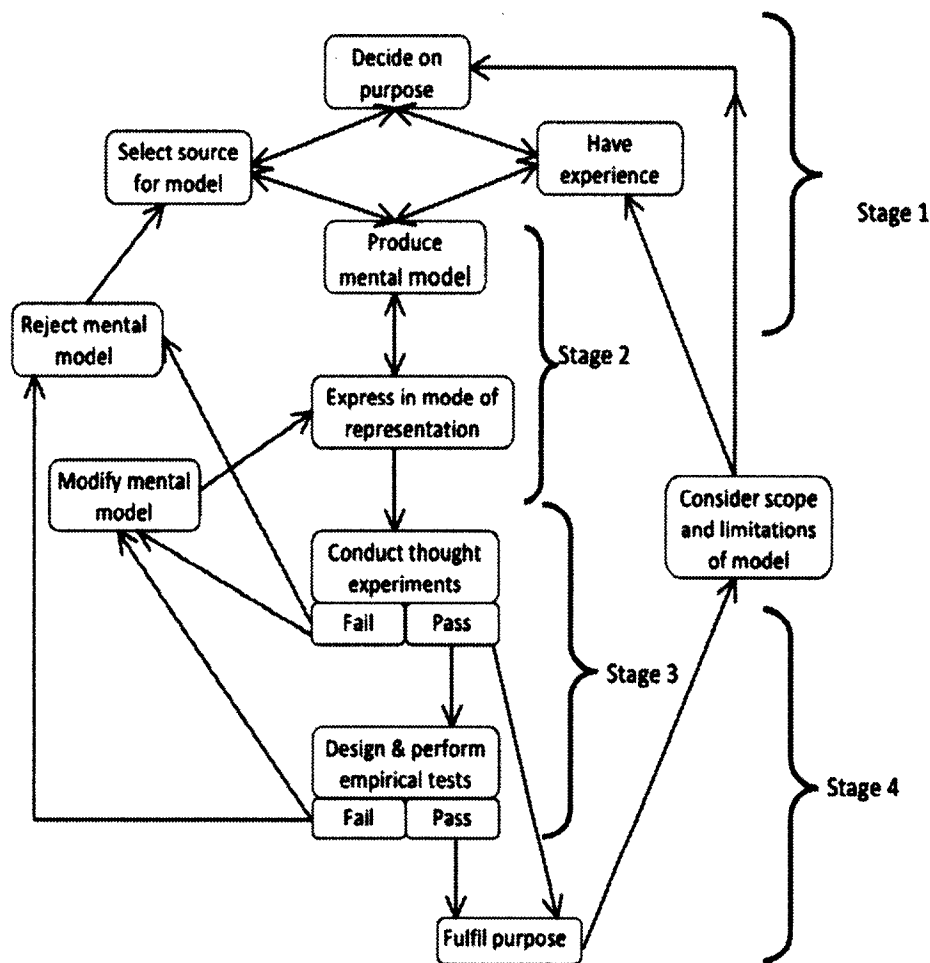


Figure 2. Model of Modelling Diagram (MMD) (Justi & Gilbert, 2002).

This study also assumes that though educators try to reach a certain level of authenticity in their classrooms, the context of a professional laboratory and a K-12 science classroom is different. In particular, this study assumes that scientists and students argue in different ways. Students' arguments are more simplistic than those of scientists. Due to this, this study will use the term coined by Mendonca and Justi (2013) to characterize student arguments: Scientific Curricular Arguments (SCA). Mendonca and Justi's (2014) three levels of SCA involve the complexity of student argumentation. In level one and level two, arguments are characterized as having a sense-making purpose as opposed to the persuasive purpose of level three. More specifically, level one involves

a claim based on either a theoretical, empirical or a representational justification. Level two connects theoretical justification and empirical evidence to bolster a claim, while level three involves the components of level two, but adds in the factor of persuasion. I connect these levels to the MMD as well. Table 1 illustrates how, as research has found, (Mendonca & Justi, 2014; Passmore & Svoboda, 2012) persuasion (Level Three) is more commonly associated to the last two stages in the modeling process.

Table 1.

Theoretical relationship between the MMD and SCA

MMD Stages of Development	SCA Levels Commonly Present
Stage 1 and Stage 2	Level 1 and Level 2
Stage 3 and Stage 4	Level 1, Level 2 and Level 3

The frameworks provided here assisted in the development of two research questions:

1. How does a design-based modeling intervention involving the design and use of multiple models impact the spatial abilities of middle grade students?
2. How does a design-based modeling intervention involving the design and use of multiple models impact modeling-based argumentation of middle grade students?

Overview of Study

This research was a case study of seven students who participated in a four-day, design-based modeling lesson designed to challenge students to use 3D technologies, and several other tools to design several different models in order to argue their models' plausibility. The lesson involved students in exploring the interrelatedness of the environment and an animal's form and function. Data were collected through the use of the Mental Rotations Test (Vandenberg, Kuse & Vogler, 1985) and the Revised Purdue

Spatial Visualization Test: Rotations (Yoon, 2011) as a pre/post measure, pre-post interviews, video observations, and student artifacts. Analysis involved determining spatial performance before and after intervention, qualitative analysis of argumentation through the use of the Instrument for the Analysis of Scientific Curricular Arguments (IASCA) (Mendonca & Justi, 2014), and qualitative analysis of interviews, observations and student artifacts to develop a rich understanding of how each case's spatial abilities and model-based argumentation was impacted.

Chapter 2: Literature Review

This chapter will first present existing research on the five main foci of this study:

(1) modeling and models in science education; (2) engineering design challenges in science education; (3) modeling as a component of engineering design; (4) models as used in scientific argument; and (5) spatial abilities. During the search for relevant literature for this review, I searched peer reviewed science education, engineering education and technology education journals in order to gain a more complete view of how modeling and design are viewed in each of those fields. To make sure the findings were current, when possible I used only those published within the last ten years.

Defining Modeling and Models

There is some confusion in the definitions of modeling and models across science and engineering education contexts. In science education, modeling and models are typically viewed as an authentic scientific process and/or product on their own, while engineering educators tend to view modeling and models as authentic components of design process. Some educational researchers define modeling as both a process and a product (eg. Mentzer, Huffman, & Thayer, 2014) while others deem modeling as process and model as outcome (eg. Chang, Quintana, & Krajcik, 2010). While some researchers describe models as explanatory, predictive and functional (eg. Hoskinson & Couch 2014), others describe them as tools to explain, predict and describe (eg. Mentzer et al., 2014). These and countless other fundamental differences in definitions can cause confusion among researchers and practitioners alike. Passmore and Svoboda (2012), contend that educators' confusions of the definition and uses of scientific models can lead to a less authentic portrayal and practice of modeling in curriculum which can then lead

to students misunderstanding the nature of scientific modeling and the nature of science altogether. However, Hoskinson and Couch (2014) claim that though educators must be wary of the specific differences in modeling practices across disciplines, similarities in modeling across science disciplines can provide a much needed link for students.

This study's definition of modeling and models was adopted from Gilbert and Boulter (2000). They provided a thorough description of the different ontological classifications of models (Table 2) and several different modes of representation displayed through expressed models (Table 3) and then typologies concerning the different modes. First, I will describe the ontological classifications of models as presented by Gilbert and Boulter (2000). Gilbert and Boulter (pg15) describe a mental model as a "private and personal cognitive representation" that an individual may hold about a phenomenon. Once this representation is publicly presented, it is an expressed model. The presentation of the model alters it in two ways: (1) A mental model is too complex to publicly represent in an exact fashion, so important abstract components are omitted or altered, and (2) going through the process of expressing a mental model allows one to grapple with their own conceptions thus changing these conceptions. Through discussion and scientific tests, different groups might modify and/or accept components of an expressed model. Once agreement between several groups occurs, an expressed model changes to a consensus model. This directly relates to the social constructivist framework that states that students work together to solve problems (Vygotsky, 1994). Discussion and critique are important to this framework so that students are involved actively in the learning process while the teacher facilitates learning (Schnittka and Bell, 2010). Through formal scientific testing, further discussion and agreement within the

scientific community, a consensus model can become a scientific model. As described, this process of modeling, is a complex, nonlinear and iterative process involving among other things, information gathering, scientific investigation, scientific discussion and the creation and modifications of models.

Table 2.

Description of Model Classifications (Gilbert and Boulter, 2000)

Ontological Classification	Description
Mental	A private model that is an individual's conception of a phenomenon
Expressed	The public expression of a mental model (understanding that a mental model cannot be expressed in totality or with complete accuracy)
Consensus	An expressed model that has undergone discussion and scientific testing and is agreed upon across several social groups
Scientific	A consensus model that has underwent formal scientific testing and discussion may lead to the scientific community agreeing on a model making it a scientific model

The representation of a model can be expressed in five modes: concrete, verbal, mathematical, visual, and gestural. A concrete model can be either two-dimensional or three –dimensional and may be constructed from various materials. Another mode of representation is the verbal mode. This is when one verbally relates something to another well-known concept either in writing or through speech. Mathematical modes of representation use equations or numbers to explain or describe phenomena. Drawings, diagrams, and graphs are visual modes of representations, while gestural movements, like

hand motions, constitute the gestural mode (Gilbert & Boulter, 2000). All of these modes may overlap and intertwine with one another during the course of scientific modeling.

These modes of representation and their respective descriptions are shown in Table 3.

Table 3

Expressed models modes of representation (Gilbert & Boulter, 2000)

Mode of Representation	Description
Concrete	A representation made of tangible materials
Verbal	A verbal relationship between phenomena and a well-known concept or object.
Mathematical	Descriptive or explanatory mathematical expressions
Visual	Graphs, diagrams or graphical pictures
Gestural	Actions representing phenomena in some way

Modeling and Models in Science Education

Modeling and models are considered authentic and meaningful practices and products of scientists. Many science educators also contend that modeling and models are a crucial aspect of scientific literacy (Linn, 2003; Gilbert & Boulter, 1998). Therefore, bringing modeling and models into science classrooms seems an obvious goal for educators. One strategy to bring modeling and models into educational practice is Modeling-based Learning (MbL). After a thorough review of MbL studies, Loucha and Zacharia (2012) claim that there is an agreement in the four basic steps of modeling among educational researchers: (1) collecting information about the phenomena; (2) creating a model based on information gathered; (3) evaluating the model for usefulness

in the context; and (4) revising the model. Though it may appear as a linear process, MbL is described as an iterative process where students continuously repeat (not necessarily in a linear fashion) the steps to improve their model, making it more complex (White & Fredrickson, 1998) and constantly compare their model to the phenomena (Constantinou, 1999).

Research on the impacts of MbL has shown positive results in the area of student learning of content knowledge. Through qualitative methods Barab, Hay, Barnett and Keating (2000) found that students gained a rich depth of science conceptual knowledge when they constructed concrete models. This finding is similar to Hansen, Barnett, Makinster and Keating's (2004) study comparing traditional and model-based curriculum of undergraduate college students. Hansen et al. (2004) found that students in the traditional astronomy classroom displayed better factual recognition and general understandings of the material while the treatment group developed a more in-depth understanding of spatial relationships. Dede, Saltzman, Loftin and Sprague (1999) found that developing 3D models provided students a better conceptual understanding than 2D models of the phenomena being represented. This is concerning understanding that there is a great imbalance between 2D graphical modeling and other modes of modeling in schools (Mentzer, Huffman, & Thayer, 2014). Lehrer and Schauble (2000) state that younger students often find it frustrating or confusing that a model does not exactly match a phenomena. Because prefabricated models can foster misconceptions for students, Penner (2000) highlights the importance of students creating their own models in order to understand the phenomena behind its creation and the limitations of models.

Though Loucha and Zacharia (2012) mention the small amount of research on Model-based Learning using modeling software, this area in the literature is beginning to emerge. Their findings in 2009 demarcate the processes in which students frame their work using this software: procedural, causal, conceptual or technical. Each of these different processes result in a different outcome. In a case study involving PhD engineering students, Zhang, Liu and Krajcik (2006) found that when using the Model-It computer software, expert modelers go through a linear process beginning with an operationally defined focus and then moving through planning, building, and testing models without a great deal of iteration. They also found that expert modelers develop thorough arguments to support their model and modeling process.

Definition of Engineering Design Challenge

Many different terms have been used in concordance or in place of the phrase engineering design challenge that represent a similar, if not an identical instructional approach. Dym, Agogino, Eris, Frey and Leifer (2005) described their approach to engineering design in the classroom as Project-based Learning (PBL) with the caveat that the project was design based. Cantrell Peecan, Itani, and Velasquez-Bryant (2006) designated the implementation of a design activity as interactive learning activities while De Romero, Slater and DeCristofano (2006) called their design activities a design challenge. Each of these studies dealt with small groups of students working together to solve a problem through design process. For the purposes of this study, I define engineering design challenges as a pedagogical approach in which small groups of students work together to design a solution in the form of an artifact to solve an ill-structured problem.

Engineering Design Challenges in Science Education

Petroski (2003) noted children's natural proclivity to build things and described them as "born engineers," yet until recently engineering education was reserved for elective classes or classes for advanced students in special schools. In recent years reform in science education has called for the incorporation of engineering content and practices within the science classroom (eg. NGSS Lead States, 2013; NRC, 2012). Engineering design challenges are one method that allows teachers to incorporate engineering in their science classes. Many studies have attempted to investigate the impact of engineering design challenges on student gains in science content knowledge. Apedoe, Reynolds, and Ellefson (2008) found that high school students who previously had difficulty learning difficult core concepts in chemistry after six months of traditional curricula, made significant gains after only eight weeks completing a design based challenge. In a study of high-needs eighth grade science students, Silk and Schunn (2009) reported significant gains in the science content knowledge of their participants as compared to traditional curriculum. These studies employed a pre/posttest design where the instruments were multiple-choice assessments meant to measure specific content knowledge.

Researchers also investigated the demographics of students obtaining science content knowledge gains. Findings on the impact of engineering design challenges on the achievement gap are mixed. Silk and Schunn (2009) found that while all students measured significant gains, the achievement gap between African American and /or students with low economic status and their Caucasian counterparts remained. However, as compared to scripted inquiry, Mehalik, Doppelt and Schunn (2008) found that low achieving and middle achieving African American students had the most significant

science content gains when involved in design challenge pedagogies. In a related study, Mentzer, Becker and Park (2011) found that science grade point average (GPA), not math or communication GPA, of the previous year was a significant indicator of student performance during design challenges. Fortus et al. (2012) found that students were able to transfer their science content knowledge in order to solve another challenge unlike the first. These studies all involved a pre/post test design.

In a study investigating how expert and novice designers engaged in the process of engineering design, Crismond (2001) found that novice designers used science content knowledge to support their design much less than expert designers (Crismond, 2001).

Modeling as a Component of Engineering Design

Modeling is coined as an integral component of both science (Svoboda & Passmore, 2013) and engineering education (English, 2008). Similarly, in their book, *Developing Models in Science Education*, Gilbert and Boulter (2000) assert that modeling and models can provide a bridge between science and engineering education. Most often, models in engineering design are represented in either the visual (sketches, drawings or diagrams) or concrete modes (3D models), but they may come in any mode.

Several forms of design-based instruction involve the construction of models. Design Based Science (Fortus et al., 2004), Learning by Design (Kolodner et al., 1998) and design-based modeling as described by Penner et al. (1997) are a few such design-based instructional methods. Through these methods of instruction students construct some sort of model in order to learn science concepts. In these methods of instruction, models are constructed, and when possible, subjected to testing, and presented in some way to the teacher and others in the class.

Though both engineering education and science education literature mention models as crucial in students' development of engineering and scientific understandings, the approach toward the use of models in each context is very different. In order to provide teachers a means to bridge the gap between engineering and science education as standards now call for in the NGSS (Achieve Inc., 2013), instruction that blends approaches of both engineering and science education may provide a powerful and seamless integration of the disciplines, yet the difference in the use of models across domains must be noted and expressed with students. In biology education, models are typically 2D and used to represent exact placement of components of the organism. This differs from models in physics and engineering that are used to generate ideas or solutions to test. In this study, participants used biological models to test ideas much like models from physics education or engineering education.

According to Macdonald and Gustafson (2004), research related to design practices dealing with student drawing have been mainly in four areas: the link between drawing and making, the link between 2D and 3D drawing, the role of drawing in creating and developing ideas, and the explicit teaching of drawing. Macdonald and Gustafson (2004) mention that when offered a choice, students quickly choose 3D modeling over 2D sketches though the simpler sketches allow for more abstract idea generation.

Chang et al. (2008) report that results in 3D modeling of chemistry concepts were promising when using models to support students. Research on the effectiveness of computer aided design results are mixed, but Klahr, Triona and Williams (2007) found

that in both learning and confidence measures there was no significant difference between hands on and virtual materials.

Another technology present in professional engineering that deals with modeling is 3D printing. Today, engineers use 3D printers to print out design prototypes and sometimes print the actual product needed to solve a problem. 3D printing provides a unique opportunity for science education because it involves virtual materials in the designing portion, but then transforms virtual design into a tangible creation. However, research related to this new technology in K-12 education is scant. There is much to learn about how this technology can impact student learning. Horowitz and Schultz (2014) posit that the technology allows for inexpensive hand-held models of terrains of celestial bodies not readily available otherwise. Studies like this can elucidate the educative advantage of students being able to design customized models to enhance their understandings of specific topics.

Paper Drawings

Paper drawings have been used in both science and engineering education contexts as educative tools. In science education, paper drawings are often associated with models and/or modeling either in a generative or representational role (eg. Louca and Zacharia, 2012). In these contexts drawings are effective tools to uncover students' conceptual understandings and to facilitate communication about those understandings (Chang, 2012). Engineering education researchers also focus on drawing as a modeling tool in the presence of engineering design. As engineering design enters the contexts of science education, the lines of inquiry converge. MacDonald and Gustafson (2004) found that teachers approached drawing in the classroom as a representational activity more often

than as a generative one. They argue that students should also use 2D drawing as a way to generate ideas. However, Bamberger and Cahill, (2013) mentioned diagramming as a generative component of their strategy to present design process to students. Bamberger and Cahill (2013) noted that students tended to spend little effort on their paper drawings unless they were provided a scaffold that assisted not in drawing technique but in thinking through their design before drawing. However, Macdonald and Gustafson (2004), maintain that the explicit teaching of drawing may assist students in utilizing drawing in a more effective way.

Ramadas (2009) noted that though there are great similarities in science and engineering design drawings, there are vivid differences in how concepts are communicated. In particular, science drawings often combine several modalities of expressed models (eg. verbal, gestural, visual, concrete, mathematical) to convey concepts, while engineering design drawings often encapsulate conceptual content within the drawing alone. For science instruction, it is important to allow text and other modalities to accompany drawing (Ramadas, 2009).

3D CAD Drawings

3D CAD drawings or 3D computer modeling tools are usually viewed as an engineering education commonplace, but are now becoming more and more common in science education. Many engineering education studies (e.g. Toptas, Celik,& Kataca, 2012, Youssef & Berry, 2011) have investigated the use of 3D drawing in CAD software in higher education and with secondary students. Much of this research deals with spatial reasoning. Research has linked students' ability to design 3D objects in CAD software to their spatial abilities (Contero, Naya, Company & Saorin 2008; Company, Contero,

Piquer, Alexos, Conesa & Naya, 2004). Martin-Dorta, Saorin, and Contero (2008) found that a brief course involving CAD software improved spatial abilities and motivation in students. Spatial ability is considered a crucial skill for professional engineers. Miller (1996) linked spatial skills to success in professional engineering. In science education, 3D drawings are another way to create a model. Again this involves students returning to science concepts and, many times, representing those concepts in graphical or concrete form. According to Barab et al. (2000), students could gain a rich understanding of astronomy concepts when using generic 3D modeling tools.

Physical Models

One mode of an expressed model is a concrete, or physical model (Gilbert & Boulter, 2000). In the context of education, a concrete model essentially becomes an artifact that allows students to express, reflect on and critique current conceptions. If several different groups agree on an expressed model through experimentation and discussion, it can become a consensus model (Gilbert & Boulter, 2000). Gilbert and Ireton (2003) argue that it is crucial that teachers encourage students to constantly analyze their models within the modeling process. According to Roth (2001) discussion and critique are important components of the modeling process in that it keeps students involved actively in the learning process. In engineering education literature, models are portrayed in a similar light, but located within a larger design process. Carberry and McKenna (2014) delineate three uses of physical models in engineering design: to experiment, display, and imitate.

Scientists' uses of 3D physical models are an important and authentic part of their practices and they have long known and expressed the benefits of them. In his book

dealing with the construction of 3D models for use in biological chemistry, Robert A. Harte (1969), noted that compared to 3D representations, two-dimensional (2D) graphical representations were constraining when it came to both “the studying and communication of the three-dimensional world (p. 1).” Physical models also allow students to think differently about the concept at hand and to examine characteristics that may not otherwise be available in a 2D representational form. In a study where students constructed 2D drawings and their own physical models, Pavlou (2009) noted the difference in thinking as the students had to think about their representation from all sides. In particular, she described students creating animals as a 3D representation as quite a different task than drawing. In that, the 3D representations made students create representations of the different views of the animal from all sides. Without the 3D version of the model, the missing structures are either omitted completely or left for students to explain verbally. This highlights what Harte (1969) mentioned as the constraints of 2D representations on discussion.

Spatial Abilities

As mentioned in Chapter 1, students’ spatial abilities have been linked to their performance in science and math and to their interest and subsequent success in STEM careers (eg. Small & Morton, 1983). The NGSS and other science standards do not often mention spatial abilities explicitly in their standards and it is rarely mentioned in the objectives of teachers in their lesson plans. Yet research constantly professes the importance of students’ spatial abilities and also the possibility of effective training of them. This section reiterates the definition of spatial abilities and provides research related to spatial abilities in STEM education literature.

As mentioned in Chapter One, this study draws from the work of Linn and Peterson (1985) that demarcates three categories of spatial abilities: spatial perception, spatial visualization and mental rotation. Spatial perception is a category that deals with the ability to determine spatial relationships with respect to the orientation of one's own body, in spite of distracting information. Spatial visualization involves the ability to manipulate complex spatial information when several stages are needed to produce the correct solution. Mental rotation is a category that involves the ability to rotate, in imagination, quickly and accurately two- or three-dimensional figures.

There is much attention in the literature paid to gender differences in spatial abilities. In an attempt to explain males' superior spatial performance, this literature examines possible precursors and correlates for superior spatial abilities. In particular, these studies have provided data related to biological, sociocultural and experiential factors that either correlate or result in differences in spatial abilities. Within this section I will briefly summarize research on biological factors related to spatial abilities and provide greater detail on research correlating sociocultural factors, past experiences and interests with spatial abilities, as this will provide more insight into the particular study.

Lawton (2010) categorized biological factors resulting in superior spatial performance to include hormonal influences and brain organization. Many spatial abilities studies dealing with the effects of hormonal factors on spatial abilities involved rats in which hormone levels were manipulated before spatial tasks (eg. Jonasson, 2005; Saucier, Shultz Keller, Cook & Binsted, 2008). The findings in these studies suggested that rats' better navigational performance was due to exposure to testosterone or its metabolites early in development (Lawton, 2010). Spatial studies on humans with

congenital adrenal hyperplasia (CAH) suggest that levels of exposure to hormones are important to the development of spatial abilities. CAH is a condition that causes the body to produce more testosterone than normal. Males with CAH tended to perform worse on spatial tasks than males who did not have CAH. Conversely, females with CAH performed better on spatial tasks than their counterparts (Puts, McDaniel, Jordan & Breedlove, 2008). This finding suggests that there is an ideal level of testosterone that may be linked to optimal spatial performance.

Research has also linked differences in spatial task performance between genders to what parts of the brain are activated during such tasks. During spatial tasks in general, the parietal area of the right hemisphere of men's brain is more active than women's. In contrast, the frontal region of the right hemisphere is more active in women's brain than men's (Hugdahl, Thomsen & Ersland, 2006; Thomsen et al., 2000). The frontal areas of the right hemisphere are thought to be related to language function and analytical thought (Lawton, 2010). As opposed to holistic strategies, using more analytical, or piecemeal strategies, to mentally rotate figures takes longer to process and requires a more metacognitive approach to solving spatial challenges (Lawton, 2010). This may explain why males tend to describe their mental rotations as more holistic than females and may explain the greater effect sizes between males and females when spatial tests are timed.

Another explanation for gender differences in spatial abilities is the difference in the experiences of females and males. Tracy (1987) contends that one possible reason for differences in experiences is gender-typed toys and activities. The implied rules of culture often times assign toys and activities a gender-type. In the United States toys for children three to thirteen were found to be gender-typed. More masculine toys and

activities like Legos, blocks and trucks tended to involve spatial activities like construction or moving through space. More feminine toys like dolls, kitchen and stuffed animals did not involve much spatial manipulation (Tracy, 1987). In a study involving over 400 adults, Doyle, Voyer and Cherney (2012) found positive correlations between participants that were involved in more masculine activities during childhood and superior performance on spatial tests. They reported negative correlations between participants that were involved in more feminine activities during childhood and superior performance on spatial tests. Somewhat unexpectedly, their study found a negative correlation between video game play and spatial performance. This went against many previous studies (eg. Cherney, 2008; Terlecki & Newcombe, 2005) that had linked the boys' use of video games to their superior mental rotation performance. This difference may have been related to the fact that the context of video games can be extremely diverse and vary widely on the amount of spatial challenges present in the game. In fact, the aforementioned studies that found links between video game play and superior spatial performance, differentiated between games that required spatial manipulation and those that did not. Other studies (eg. Quaser-Pohl & Lehman, 2002; Voyer, Nolan & Voyer, 2000) found that when participants reported high amounts of spatial experience during childhood, differences in spatial performance among them were either small or insignificant regardless of gender. Findings such as these may better explain individual differences between participants as there are certain females that outperform high performing males on spatial tasks and many males that score lower than most females on spatial tasks. Due to Sherman's (1967) Bent Twig theory, one cannot completely rule out the presence of biological factors in the interests and choices of children as to what

activities in which they are involved. This theory highlights certain children's bend toward and subsequent participation in spatial activities. For example, one that has innately high spatial ability will choose activities that involve more spatial manipulation than those without such innate ability. Therefore, those that have innate spatial ability are more inclined to choose activities that will enhance or hone those abilities further widening the gap between people's abilities. Due to research findings such as these the US National Research Council of the National Academies (2006) recommend spatial training for all students.

When thinking about the skills involved in spatial ability and the various science concepts we want students to learn, it is interesting that much research has revealed a positive correlation between students' performance on spatial ability tests and their performance on science content tests (eg. Bodner & McMillen, 1986; Staver & Jacks, 1988). Researchers have also found that building spatial ability through instructional methods can increase science learning achievement (Small & Morton, 1983; Tuckey, Selvaratnam, & Bradley, 1991). Though researchers have investigated the relationship between spatial reasoning and science learning, much work still needs to be done. Some believe transformational reasoning is a major link between the two.

Transformational Reasoning

Ramadas (2009) describes model-based transformational reasoning as a negotiation among visual-spatial thinking and other types of reasoning (eg. verbal, gestural) in the context of one or more models. In his review, Ramadas gives several examples of scientists using model-based transformational reasoning as a tool for progression in science. One such example in the context of evolutionary biology deals

with Thompson's (1961) theory of transformation. Over the course of many years work from several different people in various contexts, animal drawings from observations gradually became idealized drawings of many species which then led to comparisons and coding of certain aspects of each species. After an in-depth comparison of species' anatomy by the work of Georges Culver (1769-1832), Thompson's theory of transformation, where he calculated evolutionary changes in animals using mathematics emerged. As this example illustrates, this ability to transform different models into other forms, or model-based transformational reasoning is evident in the progression of science. Similarly, in an educational context, images and models can hold abstract metaphorical meanings that can elucidate students' deeper thoughts or allow students to communicate and expand on concepts (Tversky, 2005). Tversky's assertion illustrates that model-based transformational reasoning allows for and possibly inspires a desired depth of conceptual learning.

Similar to Tversky's statements, Gilbert and Boulter (2000) state the importance of communication in students' science learning through modeling. Vygotsky (1978) proposes that through model-making, cognition can be mediated in a social context where the learner can engage in visualization and communication of ideas with others. This can lead to the effective and efficient solving of problems (Heiser, Tversky & Silverman, 2004). With the importance of inquiry in science education reform, and the classic cycle of observation, description, prediction, and explanation of observed natural phenomena in inquiry-based teaching (Ramadas, 2009), understanding how students go about transformational reasoning is of utmost importance in contemporary science education.

Ramadas (2009) calls for studies to reveal the role of various models in mediating science learning.

Some of the findings involving transformational reasoning deal with how students explain and reason using different forms of modeling. Subramaniam and Padalkar (2009) found that when attempting to explain the phases of the moon, their participants needed to couple their verbal representations with either gestural or visual models to present their conceptual knowledge and also to reason through certain problematic or alternative conceptions. Body gestures, like the ones described, often simulate a dynamic situation and facilitate transformation between the situation and the model (Ramadas, 2009). Subramaniam and Padalkar (2009) also noted that some of the alternate conceptions held by participants involving moon phases may have been facilitated by common 2D representations of moon phases that exaggerate or represent a faulty scale of and between celestial objects. Transformation from 2D to 3D representations is thus crucial for true understanding of some concepts. Several studies found that though it was important for science understanding, many students have great difficulty moving from 2D to 3D representations (eg. Freedman, Gellar, & Kaufmann, 2010). This is concerning knowing that typically science instruction involves students in creating 2D representations without a focus on transforming it to 3D representations. Eriksson et al. (2014) found that in order for transformational reasoning to occur, students needed to encounter 3D models and representations from different viewpoints. Eriksson et al. (2014) also pointed out that motion parallax, where perspectives of students change as they virtually or literally travel around the objects of interest, was of great importance. Even with these experiences though, Eriksson et al. (2014) describes the learning process as longitudinal involving an

enmeshment of content knowledge and spatial ability. In fact, they purport that utilizing educational tools able to provide representations that facilitate the extrapolation of three-dimensionality from 2D models is integral in attaining desired conceptual knowledge of the universe.

Building Spatial Abilities

The research on how to facilitate spatial ability gains is somewhat divided, but most researchers agree that training can build spatial ability. Due to the abstract nature of many of science concepts (e.g. movement of groundwater) that are within science standards, some science educators contend that all levels of formal education should provide avenues to enhance spatial reasoning (Dickerson, Penick, Dawkins & Van Sickle, 2007). There are pedagogical strategies already in place that teachers can use to help students of all levels move between 2D and 3D representations. Strategies like paper folding, paper drawings, constructing physical or virtual models, and the use of 3D models are some of the strategies a teacher may use to build spatial thinking skills (Baker & Pibern, 1997). Newcombe (2010) suggests that students in primary and elementary grades can build their spatial abilities by drawing, mapping, engaging in measurement and using recreational software that has them see different viewpoints of shapes and objects. In a study involving approximately 1,000 students from fifth through eighth grades, Ben-Chaim, Lappan and Houang (1988) found that after an instructional intervention incorporating tactile manipulation of geometrical objects, all grade levels made significant gains in spatial visualization skills as measured by the MGMP Spatial Visualization Test. This finding is interesting when understanding that the MGMP Spatial Visualization Test measured mental manipulation of geometric objects instead of tactile

manipulation. Another interesting finding in this study was that though girls did not perform as well as boys on the spatial test, they did make significant improvement and researchers suggested that they learned in much the same way that boys did in this respect.

Research has linked students' ability to design 3D objects in CAD software to their spatial abilities (Contero et al., 2005; Company et al., 2004). Martin-Dorta, Saorin, and Contero (2008) found that a brief course involving CAD software improved spatial abilities and motivation in students. In contrast, Shavaliel (2004) conducted a 13 week study using CAD-like software with a visualization component to allow fourth, fifth and sixth grade participants to interact with their designs in a virtual walk-through. The researcher guided the participants through different activities using the software for one hour every week to better their spatial abilities. In this study there were no significant gains in spatial abilities over the control group. A limitation of this study that could have impacted findings was that students worked in pairs on the computer to manipulate the software. This may have watered- down the intervention and lessened the impact of the software on spatial learning. Spatial ability is also related to how easily it is for one to learn to use computer aided design software (Hamlin, Boersma, & Sorby, 2006) and to perform complex database manipulations (Norman, 1994).

Scientific Argument

In science education literature there are various definitions and explanations to describe scientific argument and scientific argumentation. Kuhn (1992) describes the common and traditional view of argument as rhetorical where an authoritative figure uses argument to persuade others of the strength of their case. He believes this definition

originated from positivist notions that science and scientific knowledge is infallible. This is common in traditional science classrooms where scientific discourse usually consists of a teacher didactically presenting scientific concepts to students that have no recourse to argue the validity of such information Norris (1997). Yet, today a central goal of science education is that teachers provide students opportunities to question and evaluate claims and essentially become scientifically literate citizens (NGSS Lead States, 2013). Driver, Newton and Osborne (2000) described a multi-voiced interpretation of argument that involves the examination of several perspectives in order to reach agreement. This study is informed by the latter interpretation of argument which finds its theoretical underpinnings based in Vygotsky's (1978) social constructivism. More specifically, this view defines scientific argumentation as a social process in which empirical and theoretical justifications support or refute claims in order to assess knowledge (Erduran & Jimenez-Aleixandre, 2008).

Research on scientific argumentation of K-12 students consistently reveals that they have difficulty with argumentation. Students tend to focus on making their claim sound, while usually dismissing others' refutations or counterclaims with little thought (Pontecorvo & Girardet, 1993; Jimenez-Aleixandre et. al, 2000). Students have problems developing evidence-based arguments (Kelly, Druker, & Chen, 1998) and reasoning between alternatives in inquiry settings. In a similar study focused on developmental issues of argument, Felton & Kuhn (2001) found that adults tended to use more counterarguments, adapted their argument to consider the audience and made attempts to weaken their opponent's claim more than adolescents. Yet studies have found that

children as young as five years old can develop justifications and counterarguments (Anderson, Chinn, Chang, Waggoner & Yi, 1997).

Although scientific argumentation is seen as crucial in developing scientifically literate students, students seldom are provided the opportunity to take part in argumentation in K-12 schools. One reason is because teachers are apprehensive about allowing it to happen in class. Simon, Erduran and Osborne (2006) found that teachers were apprehensive at first about using an argumentation method of instruction because they felt that it would teach alternative explanations. After using an argumentation method of teaching science, teachers were relieved and complimentary of its effectiveness.

Providing students the opportunity to engage in argument can increase their argumentation abilities. The use of scaffolds is one method to combat these weaknesses. Scaffolds using computer (Sandoval & Milwood, 2005) and written tools (McNeill, Lizotte, & Krajcik, 2006) have been found to improve students' arguments. Also, explicitly teaching scientific argument components has been found to increase argumentation abilities among students (Osborne, Enduran, & Simon, 2004). Teaching strategies like Science Writing Heuristics (Kingir, 2011) and A Competing Theories Strategy (Bell & Linn, 2002) were also found to help students become motivated and to develop better arguments.

Model-based Argumentation

In modeling contexts, it can be implied that arguments would support or refute a model, or an aspect of a model (Bottcher & Meisert, 2010). For example, model-based arguments may justify the appropriateness of a model to represent a particular

phenomena (Giere, 1999). Mendonca and Justi (2014) describe the four different situations in which a model might be involved in scientific argument using a modified version of Baker's (2009) figure on argumentation and theory. Figure 3 illustrates the four different situations in which a model can be argued. Figure 3 assumes that more than one model could exist for the same phenomenon. Situation one involves two parties arguing for the acceptance of two different models and situation two one party is arguing for the acceptance of a model while the other refutes the model. In situation three a person has doubts whether model one or model two best represents the phenomena, while in situation four a person is conflicted as to whether to accept or refute model one. In both situations three and four there must be doubt in the mind of the person.

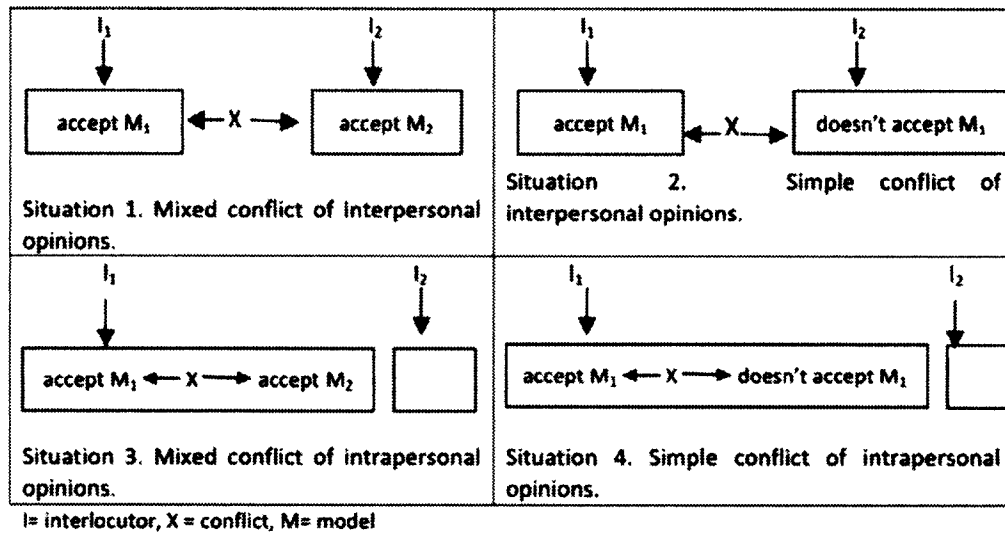


Figure 3. Model-based argumentation situations (Mendonca & Justi, 2014)

There is little attention in science education literature on the relationship between modeling and scientific argumentation. In a study involving high school chemistry students, Maia and Justi (2009) found that during modeling students were involved in argumentation at every stage of the modeling process. They also found that persuasion

and arguments occurred more frequently as students tested or evaluated their models.

While students were constructing their model, argumentation usually dealt with the construction of explanations as opposed to persuasion (Mendonca & Justi, 2014). In their study, they also found that several modes of models assisted the teacher in communicating her ideas and understanding the students.

Chapter Three: Methodology

This chapter explains the methodology of this study. It provides a statement of purpose, research questions, a description of the research design and explicates the roles of the researcher. It includes the research plan, data sources, and collection and analysis procedures. It is organized chronologically, in that it begins with theoretical perspectives and underpinnings that informed the design of the study, then provides the research questions, then moves to a description of the specifics of the design, and finally ends with data analysis methods. Within the specifics of the described study design, is the setting and context in which it was conducted in order to assist the reader in developing a clearer illustration of how the researcher conducted the study. The reader can find examples of several data sources in the appendices.

The purpose of this study was to investigate the impact design-based modeling instruction had on the spatial abilities and model-based argumentation of seventh grade students. In particular, the design-based instruction in this study involved students in iterative model design and construction in order to explain and argue their ideas. The investigation involved two research questions:

1. How does design-based modeling that involves the design and use of multiple models impact the spatial abilities of middle grade students?
2. How does design-based modeling that involves the design and use of multiple models impact modeling-based argumentation of middle grade students?

Research Design

The philosophical grounding of this study is best described as pragmatism. Pragmatism is not wholly committed to any one philosophy or reality. Rather than focusing on the importance of using a particular method, this research was designed with the primary concern of finding methods that best solve the research problem or answer the research questions (Creswell, 2013). With this perspective, the research design involved both qualitative and quantitative methods of data collection and analysis.

In particular, the design and selection of qualitative methods for this research were primarily rooted in the philosophy of social constructivism. This assumes that people socially construct knowledge as they strive to understand the world around them. Individuals or groups construct and reorganize their belief systems as they subjectively make sense of their experiences (McMillan & Schumacher, 2006). This design allowed for data collection through social interaction in participants' specific context in order to better understand the complexities of participants' views. The design and selection of quantitative methods of this research were primarily rooted in postpositivism. Quantitative data collection and analysis involved logical and systematic steps based on prior theory and previously validated instruments (Creswell, 2013).

A mixed method comparative case study design was employed in order to investigate the research questions (Yin, 2003). Case studies rely on multiple data sources to provide rich description of phenomena (Yin, 2009). A mixed methods design was appropriate for this study because it allowed for different types of data to converge on the same research question allowing for "investigators to collect a richer and stronger array of evidence" than what is allowed with one method (Yin, 2009, p. 63).

Role of the Researcher

The role of the researcher was to develop the research study and several data sources to accompany it, to implement the intervention, and to analyze and interpret the findings from all data sources. The use of human subjects also obligates the researcher to protect all participants. The researcher obtained an exemption from the Old Dominion University's Human Subjects Review Committee so that the study was not required to undergo Institutional Review Board review. The participants and their parents all signed a consent/assent form giving the researcher permission to record video and audio of observations during the intervention and interviews before and after the intervention. All data sources were locked in a password-protected file on a locked computer. The researcher also maintained the confidentiality of participants by establishing pseudonyms to attach to all data sources. Participants or their parents were able to discontinue participation at any time in the process. It was also important for the researcher to make all attempts to protect the reliability and validity of the study's findings. This means that any biases that the researcher had throughout the study were bracketed. The researcher was an elementary school teacher for fifteen years in an affluent area in the Mid-Atlantic region of the United States. As such, the researcher had prior knowledge of developmental characteristics of children and had to bracket any biases he had toward private school students as opposed to public school students.

Participants

The participants (cases) in this study consisted of a total of seven seventh grade students from a private school in the Mid-Atlantic region of the United States. The researcher selected this particular school due to the relative convenience of the sample

and for their willingness to work with the researcher. Because students attending this school pay tuition and are accepted after application to the school, this sample could not be considered a representative sample of the general population. The use of multiple cases was based on replication logic (Yin, 2009). Each participant represented a holistic case within the specific context of the intervention. With replication logic, a particular basis for selection is that each case is considered a literal replication study in which similar results may occur (Yin, 2009). Each of these cases were high-achievers in science as evidenced by their exceptional grade point average in their science class. Also, they underwent the same intervention within the same context. This design allowed for both within-case and across-case comparisons (Yin, 2009). The researcher randomly assigned participants, by use of a random number generator, to working groups for the intervention. Two groups consisted of two participants while one group consisted of three participants.

Table 4 illustrates the specific demographics in each class in which we collected data.

Table 4.

Case Demographics

Pseudonym	Group	Sex	Age	Ethnicity	Science Current AVG
Billy	G1	M	13	White	95.8
Chase	G2	M	13	White	96.9
Garrett	G3	M	13	White	95.0
Greyson	G2	M	13	White	99.1
Logan	G1	M	13	White	98.9
Preston	G3	M	13	White	95.6
Tyler	G2	M	13	White	95.8

Context of the Study

The implementation of this study occurred over eight days in the course of three weeks in a science classroom. The pretests and pre-interviews were given during two days within the first week, the intervention encompassed four days during week two, and the posttests and post-interviews occurred over two days during week three. Participants were a part of a science extension group comprised of members that had the highest science averages in their class. These participants often met during their a study hall period to complete teacher-facilitated challenges where they were given opportunities to work as a team to enhance their science understandings. The intervention lasted for approximately four hours and spanned four days. Participants met together with the researcher from Monday to Wednesday and then again on Friday. On Thursday participants did not meet so that the student-created models would have time to be printed

on the 3D printer. The classroom was large and had rectangular laboratory tables that could easily be moved in order to facilitate small or large groupings of participants. On days that small groups were designing models, the tables were arranged so that each small group was a fair distance from the others. On days when the class was meeting as a whole group, two tables were put together and participants sat in a circle around them. In this way all participants faced one another in order to encourage engaged discussion.

The focus of the intervention involved the beginning portion of a larger design-based modeling science lesson that addressed the NGSS performance expectation, “MS-LS4-4: Construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individuals’ probability of surviving and reproducing in a specific environment (NGSS Lead States, 2013, p. 74).” This specific focus of this study dealt with the design of a model that related a fish’s form and function to an environment. In order to better explain the context, the intervention is broken into days.

Day 1. As with design-based modeling (Penner et al., 1997), students were presented a design challenge. The researcher read the challenge aloud from their activity guide located in Appendix A. The challenge was to modify a given fish model that could represent their ideas about how and why traits of an animal can change over time through evolutionary mechanisms of change. I told the participants that they would first focus on the parts of the given fish and how they relate to a new environment. Later they would focus on whether the underlying mechanisms of evolution could explain their development. Stratford, Krajcik, & Soloway (1998) state that students cannot proceed with the development of the underlying mechanism of a system phenomena

unless they first identify its parts and the relationship between them. Because this modeling exercise was relation based modeling, created models would present scenes of the phenomenon. The two scenes are how the fish looked in one environment and then how the fish looked in another environment. This does not explain the mechanisms involved, but the model is appropriate for explaining how the form and function is related to the environment. After this intervention the teacher would continue the lesson highlighting the evolutionary mechanisms of change.

The students were given the fish's present environmental characteristics and the environmental characteristics 500.000 years from now. Using their prior knowledge students first came up with their own paper and pencil drawing which was their first expressed model. Then each group discussed their model with their fellow group members and came to consensus on what characteristics of each model they would use for their final model. After that, the groups were allowed to redraw their fish on Tinkercad (CAD software program). The researcher then provided the students a brief tutorial (10 minutes) to assist them in reviewing all tools on Tinkercad. Students then began to design their own 3D print on the design software. The class ended with students sending the researcher the file to print on the 3D printer.

Day 2. On day two students entered to find their 3D printed models. Students wrote explanations for how and why they changed their models on chart paper and then hung them above their printed and drawn models. The teacher then had students complete a gallery walk in order to take notes on design components of other groups that they may

want to discuss as a whole group. Students then participated in a structured whole-group discussion of their models.

From listening to the groups' alternative conceptions on Day 1, the researcher developed one investigation and one presentation that would help to address some of the inaccuracies in their explanations. First, students investigated how different structures might be able to capture prey underneath sand. Students completed trials using different structures to capture prey. Each trial was timed and video recorded for later data analysis. While conducting the investigation, students created data tables, recorded and analyzed data, and made conclusions in order to make inferences about what types of structures might work best for their fish. Next, the researcher introduced vocabulary and concepts that students seemed to have difficulty remembering or understanding during day one and two (eg. selection pressures, directional selection, disruptive selection, stabilizing selection).

Day 3. On Day 3 the researcher began by allowing students 10 minutes to make modifications to their original paper drawing having now taken part in a structured class discussion, investigated several physical attributes of fish in similar environments and had been introduced to new vocabulary. While redesigning their fish, the researcher reminded students that the focus at this point was to develop strong arguments that dealt with the relationship between the form and function of the design structures of the fish and the environment. I reiterated that they should keep in mind that they will use these same models to develop strong arguments that describe how and why such changes could have occurred. In this way I hoped that students would develop their fish model with

evolutionary theory in mind. Groups were then allowed one hour to complete their design on Tinkercad software, and to formulate explanations to post on chart paper.

Day 4. When students entered the classroom on Day 4, their 3D printed models were awaiting them. Students discussed their printed models within their groups and then placed them on display below the explanations for physical structures that they developed the previous day. Each group again rotated to other groups' display to discuss and to take notes on the physical features of the printed models in order to ready themselves for discussion and defense of their own designs. During the final structured whole-group discussion, each group took turns discussing their model and fielding questions and concerns dealing with their design or the explanations behind their designs.

The day ended with a debriefing session where all participants discussed what about the intervention seemed to help them learn about engineering or science, how their group worked together as a team, and how they would like to change their design if they had another chance. Each participant also completed an exit ticket to expand on the discussion.

Data Sources and Data Collection

Over the course of the study, the researcher employed the use of semi-structured interview protocols, the Mental Rotations Test (Vandenberg, Kuse & Vogler, 1985), the Revised Purdue Spatial Visualization Test: Rotations (Yoon, 2011), a spatial activity survey (Newcombe, Bandura & Taylor, 1983), a behavior observation protocol, and the Instrument for the Analysis of Scientific Curricular Arguments (IASCA). Each of these measures is described in detail below.

Spatial Abilities Measures

Two tests were used to measure the mental rotation ability of participants. The tests were administered once before the intervention and again five days after intervention. The Mental Rotations Test is a timed test that involves 20 questions (Vandenberg, Kuse & Vogler, 1985). The questions ask participants to match a drawn 3D figure with two separate rotated versions of the same 3D figure. This test was developed for those 13 or older and has a Kuder-Richardson 20 score of .88 (Shavaliar, 2004). An example of the The Mental Rotations Test (MRT) (Vandenberg, Kuse & Vogler, 1985) is illustrated in Figure 4. After the directions and a few sample problems, participants are given three minutes to complete the first 10 questions and three minutes to complete the last 10 questions.

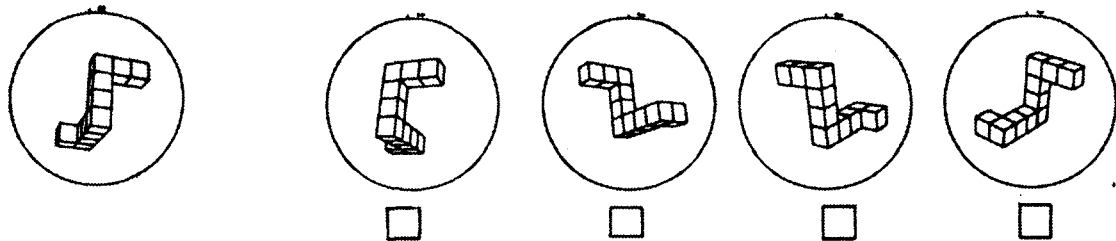


Figure 4. Example from Mental Rotation Test (Vandenberg, Kuse & Vogler, 1985).

The Revised Purdue Spatial Visualization Test: Rotations (RPSVT:R) (Yoon, 2011) orders the test items from Purdue Spatial Visualization Test: Rotations (Guay, 1978) so that the questions increase in difficulty. The questions have participants view an isometric drawing of a 3D solid and a rotated version of the same solid. It then asks participants to view another isometric drawing of a 3D solid and find the figure that is rotated in the same way. The RPSVT:R allows participants 25 minutes to complete 30

questions. In a study on college students, Maeda and Yoon (2012) found the RPSVT:R yielded a stronger Cronbach Alpha score than the previous version. The previous version of the test scored well (Cronbach alpha .79) with sixth grade students in a study by Wilhelm, Jackson, Sullivan and Wilhelm in 2013.

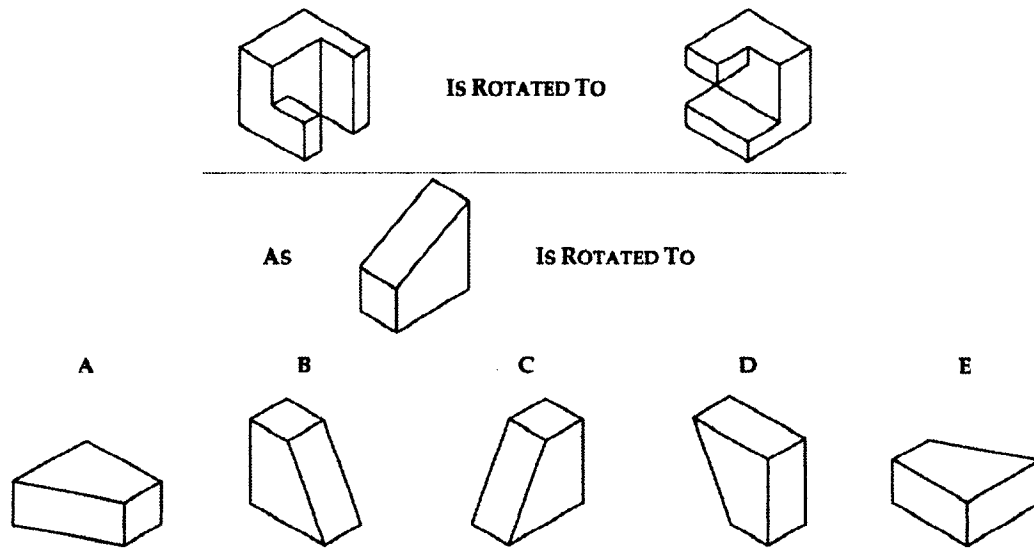


Figure 5. Example of RPSVT:R (Yoon, 2011).

In both the MRT and the RPSVT:R, the participants must rotate a given figure in their minds to solve the problem. As Maeda and Yoon (2012) purported in their meta-analysis, tests of mental rotations tend to show greater individual differences and also are useful in measuring tasks similar to those performed by those in STEM fields. For these reasons, the researcher decided to focus on mental rotations instead of other spatial abilities.

Semi-Structured Interview Protocols

The researcher developed semi-structured interview protocols for both the pre and post interviews in order to deeply explore participants' spatial experiences, confidence, interests and difficulties, participants' experiences with different types of models or modeling, and their perceptions of the use of modeling to understand concepts and argue scientifically. Current theory dealing with the study's research questions informed the development of the questions while the semi-structured design allowed for follow up questions to enable the researcher to investigate emergent themes (Creswell, 2013). Table 5 demarcates the current research that informed the development of each question. Each of these topics is covered in depth in the previous chapter. The research team reviewed and refined the initial protocol so that the questions were easy for the interviewees to understand (Creswell, 2013).

Table 5.

Development of interview protocol using research

Research	Protocol		Construct	Research
Question	Question			
	Pre	Post		
1	1,2		Spatial experience	Newcombe, Bandura, & Taylor, 1983; Doyle, Voyer, & Cherney, 2012
1	3,4	1,2	Confidence in spatial abilities	Doyle, Voyer, & Cherney, 2012
1		3,7	Spatial task interest	Newcombe, Bandura, & Taylor, 1983; Doyle, Voyer, & Cherney, 2012
1,2		4	Spatial task difficulties	Doyle, Voyer, & Cherney, 2012; Louca and Zacharia, 2012
2	5,6,7	5,6	Modeling to understand others' ideas	Louca & Zacharia, 2012; Mendonça & Justi, 2013; Gilbert & Boulter, 2000
2	5,6,7	5,6	Modeling to build knowledge	Louca & Zacharia, 2012; Mendonça & Justi, 2013; Gilbert & Boulter, 2000
2	5,6,7	5,6	Modeling to argue scientifically	Louca & Zacharia, 2012; Mendonça & Justi, 2013
1,2		7	Modeling interest	Louca & Zacharia, 2012; Gilbert & Boulter, 2000

Observation

During the observation the researcher was a “complete participant,” as the facilitator and teacher of the participants (Creswell, 2013). In order to track both behaviors and dialogue between students throughout the intervention, all possible opportunities for discussion or design were recorded on video. Using Mendonca and Justi’s study (2014) on the relationships between modeling and argumentation as a starting point to develop methods of observation, the researcher used multiple cameras to video small groups and whole group interactions to transcribe participants’ dialogue and gestures. Three video cameras were stationed at each of the three groups during group work and one camera captured all whole group activities and structured discussion. In order to gain an in-depth understanding of how participants used each of the different models during their argumentation, a behavior protocol was developed to demarcate different behaviors or gestures throughout the intervention. The development of the behavior protocol was informed by a pilot study in which participants were observed using gestures to point out structures, to simulate processes or mechanical functions of structural features of their models, and explore their own or others’ models in a tactile fashion.

Artifacts

McMillan and Schumacher (2006) state the importance of artifact collections to assist researchers in developing rich descriptions of “people’s experiences, knowledge, actions, and values (p. 356).” In this study, many artifacts were collected to add to the rich case and across case descriptions and also to triangulate findings involving how participants used certain models for argumentation and what types of spatial challenges

they experienced during the intervention. Both paper drawings and Tinkercad drawings were collected after their construction. The participant activity guides, notes, design explanations, exit tickets and the 3D printed models were collected as well. These were all collected after each day, returned to participants on the following day and then taken up at the end of the intervention.

Data Analysis

The connections between the data sources, analyses, and research questions are illustrated in Table 6.

Table 6.

Data Sources and Respective Analytic Strategies

Data sources	Analytic strategy	Research Question
Mental Rotations Test (Vandenberg, Kuse & Vogler, 1985)	Descriptive statistics	RQ1
Revised Purdue Spatial Visualization Test: Rotations (Yoon, 2011)	Descriptive statistics	RQ1
Paper drawing	Emergent codes, Content analysis, descriptive statistics	RQ1
CAD drawing and 3D printed models	A priori codes, Content analysis, descriptive statistics	RQ1

Video Observation	Emergent coding, Codes from IASCA (Mendonci & Justi 2014)	RQ1, RQ2
Behavior protocol	Emergent coding, a priori codes from pilot study, and frequency counts	RQ1, RQ2
Semi-structured Interviews	Emergent coding	RQ1, RQ2
Exit tickets, notes, design explanations, activity guides	Emergent coding	RQ1, RQ2

Quantitative analyses of both pre/post spatial abilities tests (selected answer portions) were completed. For the redrawn version of the MRT (Peters, Laeng, Latham, Jackson, Zaiyouna & Richardson, 1995), there are two correct answers for each of the 20 questions. The researcher chose to allot points only for questions with two correct answers. This meant that participants could score a total of 20 points. The RPSVT:R (Yoon, 2011) had a total of 30 questions and each student was allotted one point for each correct answer. For both tests, mean percentages of correct answers were calculated as percentages. Each case's pretest was compared to the posttest to investigate any possible change in spatial abilities. After that, the researcher calculated a composite score in

percentages for each case. This assisted in comparisons across cases. The researcher recorded patterns within the data.

Both the paper drawings and the CAD drawings were analyzed using content analysis. The analysis was informed by Insch, Moore and Murphy's (1997) steps of content analysis described in length by Hays and Singh (2012). This process included both qualitative and quantitative analyses. The unit of analyses were structures on the paper drawings and the CAD drawings. After specifying categories and generating a coding scheme, the researcher completed frequency counts (Hays and Singh, 2012). For the paper drawing and the CAD drawing, codes were first developed involving the structures located on the models. Frequency counts were then tallied for each of the codes. For the CAD drawing only, a priori codes developed in a pilot study involving the tools used in Tinkercad helped establish the majority of the codes while a few more emerged (Table 7). Frequency counts were also tallied for this to better understand the spatial tasks involved in the design of their CAD drawings. These counts were compared within and across cases and then used to assist in triangulating other data collected in order to investigate how the intervention impacted spatial abilities.

Table 7.

Cases' Use of CAD Tools

CAD tool	Description of Tool
Simple shape	Shapes to drag and drop into your design
Extrusion	A cylinder that may be extruded to create an original curved shape
Community	Pre-made shapes from other users to drag and drop into your design
Size	Pull handles to size your shapes
Hole	You can make any 3D shape into a hole
Align	Left, right or center align your selected shape in relation to another shape
x- axis translation	Move design components horizontally
y- axis translation	Move design components vertically
z- axis translation	Move design components forward and back
x- axis rotation	Rotation around the x axis
y- axis rotation	Rotation around the y axis
z- axis rotation	Rotation around the z axis

Participants' model-based arguments were analyzed using a method of analysis proposed by contemporary literature on argumentation related to modeling. Mendonca

and Justi (2014) developed Instrument for the Analysis of Scientific Curricular Arguments (IASCA) specifically for analyzing modeling-based arguments in school classrooms. The instrument allows for analysis of how Scientific Curricular Arguments (SCA) change throughout the course of the lesson, and for analysis of students' arguments dealing with the appropriateness of their model as compared to other models. The coding scheme is demarcated in Table 8. As one can see, the examples are coded to make claims and types of justifications more visual. The claims are presented in bold while the justifications are illustrated through various types of underlines. A single underline represents a theoretical justification, a double underline represents an empirical justification, and a dashed underline symbolizes a representational justification. As one can see in Table 8, a level one argument attaches either a theoretical, empirical, or a representational justification to a claim. Level two arguments involve a combination of theoretical and empirical justifications; thus making a stronger argument, while the main purpose for the argument is to make sense of the phenomena, not persuade. Mendonca and Justi (2014) describe both level one and level two as part of the sensemaking process while level three is the first to involve persuasion.

The specific coding strategies using the IASCA are now explained. After transcription of student discussions from observations throughout the entire modeling process, the primary researcher first separated argument from other discussion throughout the modeling process and then coded all arguments using highlighting to designate claims and the Mendonca and Justi (2014) proposed underlining techniques for the types of justifications. The researcher characterized persuasion in situations where students were arguing that one model was more plausible or better explained the phenomena than

another. Also persuasion occurred when a participant argued that one model was or was not appropriate to explain the phenomenon. For each argument, the researcher summarized the argument into claim, justifications, noted the context and the purpose of the argument, and noted the coherence of the argument in relation to their model. The justifications were coded into theoretical, empirical or representational. Empirical justifications in this study primarily dealt with the investigation we completed during the intervention. Statements like “The mouth design is like the tongs we used, because they picked up the most beans,” were ones that dealt with the investigation and were labeled as empirical. Theoretical justifications in this study were based on the science knowledge they had gained over the years and sometimes it was incomplete or faulty. I noted this during coding, but also looked to see if others refuted claims with faulty justifications. Noting the coherence of the argument to the model is especially important in this study because students are in the process of learning. This means the level of argument does not necessarily quantify or qualify their content knowledge or their conceptual understanding; instead it measures their argument in relation to their current science knowledge.

During analysis the researcher left room for emergent themes (Creswell, 2013). *Questioning* was one theme that emerged from the data. Many times during argument, a participant would ask a question about a model. This was not a refutation, nor a defense of the model, but it was simply an inquiry. This inquiry was important to the argument, because it often began the process of argument and also helped the researchers to understand what participants were focusing on during the viewing of models.

Engineering design was another emergent theme during analysis. During the argument, there were several instances when participants would mention design process components or speak explicitly about design issues. One subcategory of this theme was labeled *clarify challenge*. Many times the challenge criteria would surface in the argument. Examples of this were “because the prey is armored,” and “because the water was murky.” These cannot constitute as theoretical or empirical justifications, but they are constraints on the design of the model and are very important in the argument of the model. A subcategory of the theme engineering design, was *technical difficulties*. Examples of this subcategory are “I couldn’t get the teeth to work,” and “I don’t know why that didn’t print.” These types of comments dealt with students’ difficulties with the process of design or 3D printed models that did not completely match the students’ CAD drawing. *Design advice* was another subcategory that emerged during argument analysis. When participants would offer advice on how to complete a difficult design maneuver this was coded as *design advice*. One example of this was when Chase told Billy, “You could just copy, paste and align.”

After all data was coded and summarized by the primary researcher, the research team reviewed the data and their respective summaries to come to consensus on the findings. The team achieved 100% consensus on the summaries.

Table 8.

SCA Levels with Examples from Mendonca & Justi (2014)

Level	Type of argument	Description	Example
1	Theoretical (I.T)	Claim based on a theoretical justification	<u>The bond broken in the iodine cannot be ionic because it involves identical atoms.</u> (Group 2, Activity 2, claim related to the identification of the bond broken in the iodine.)
	Empirical (I.E)	Claim based on an empirical justification.	<u>Graphite consists of many carbon atoms because it does not melt when heated.</u> (Group 4, Activity 2, claim expressed after the observation that no changes were observed when graphite was heated.)
	Representational (I.R)	Claim based on a representational justification	<u>If iodine is represented by I_2, graphite is represented by C_2.</u> (Group 4, Activity 2, claim to explain the representation of the graphite in the concrete model.)
2	Theoretical-empirical (2.T-E)	Claim based on a connection between a theoretical justification and evidence	<u>The energy provided to iodine was used only to keep molecules more distant from each other; it is not enough to break the bonds because iodine has returned to the solid state after being heated.</u> (Group 4, Activity 2, claim to explain what happened when iodine was heated.)
3	Theoretical-empirical-persuasive (3. T-E-P)	Claim based on a connection between a theoretical justification and evidence aiming at persuading someone about a given model (M_X)	<u>M_4 explain the behavior of iodine. It explains its melting point because the interactions between the molecules are weak; it explains the reaction with starch because the covalent bonds between the atoms are strong.</u> (Group 2, Activity 3, claim to justify why M_4 was appropriate to explain the behavior of iodine.)
		Claim based on a connection between a theoretical justification and evidence aiming at persuading someone about the inadequacy of M_Y and the adequacy of M_X	<u>M_1 does not explain the experimental evidence; M_3 does explain it because there would be no way for the starch to react with I_2 as this form is unstable.</u> (Group 2, Activity 3, claim to justify why M_3 was more appropriate than M_1 to explain the reaction.)

Though argument did occur at points throughout the entire process of modeling, other discussion also occurred at many times during the process. These discussions as

well as the remaining data sources (i.e. exit tickets, notes, design explanations, activity guides) were analyzed qualitatively. Creswell (2013) described a cyclical process to analyzing qualitative data. This process involves organizing the data, getting a sense of the data in its entirety, forming codes to build a rich description and to develop themes within the data, interpreting the data, and representing the data (Creswell, 2013). Though preexisting theory assisted in the development of research questions and directed the study into areas in need of investigation the study allowed for emergent themes during qualitative analysis (Ezzy, 2002). Within this general philosophical framework, grounded theory uses three phases of coding: open, axial, and selective (Strauss & Corbin, 1990). During the open coding phase, the researcher searches for categories or codes and then strives to saturate the categories so that no new data can provide any new information about the category (Creswell, 2013). During the axial coding phase, the researcher identifies a single category to represent the main or central phenomena. The researcher then focuses on this category and returns to the data to see how other categories relate to or explain this phenomena (Creswell, 2013). During selective coding, connections between each facet developed during axial coding can enable the development of theory (Creswell, 2013). The researcher can now make propositions and hypotheses and/or create a conditional matrix to visualize and make sense of all the different consequences or conditions related to the theory generated (Creswell, 2013). The codebooks for this study created during this analysis are explained below.

Codebooks

During the process of modeling students were encouraged to talk with one another. Much of the talk dealt with argumentation. This talk was separated and coded

using the IASCA and emergent codes as explained in the section above. All other discussion, participant artifacts and interview data dealing with the modeling process were analyzed for emergent themes.

Design-based modeling codebook

During the open coding stage of analysis several codes were saturated with data. Axial coding assisted in developing central codes and connections to these codes were made through subcodes. The major themes will be described below, as will their subthemes.

Spatial challenges. *Spatial challenges* was a central code that emerged from the data through the observations, interview data and the student models (paper drawing, CAD drawing, 3D print). During the process of design-based modeling students were often discussing spatial topics. Examples of spatial challenges that students encountered were manipulating perspectives, proportion, depth, symmetry, balance, placement, and movement. Below, I provide examples of these subcodes.

Manipulating perspectives. In order to create a model of a fish one must think about all sides of the animal. In this way they will have to manipulate the perspective in order to create the fish; either in their mind or with the design tool. An example of this in the observation data was students using visualization tools to manipulate the perspective of their model.

Proportion. During design based modeling, students often have to deal with proportionality. An example of this in the data was when Billy notices that one pelvic fin is too small compared to the size of the body of his fish.

Depth. Participants were constantly involved in challenges dealing with depth especially when constructing their CAD drawing. In order to do this participants had to develop features that “popped out” of the 2D realm. Whenever a participant tried to portray depth in their model this subcode was used.

Symmetry. Participants also had to deal with symmetry when developing their models. For example, the eyes of a fish are sometimes symmetrical. If participants wanted to portray a fish with symmetrical eyes, they would have to go through several spatial challenges in order to align their eyes symmetrically.

Balance. In this study it was evident that students we’re challenged with the aspect of balance when creating their models. One example of this is when Tyler noticed that the front of this fish was much larger than the back of his fish. The perceived more dense front of the fish did not balance the back of the fish; hence, he was disappointed and has design.

Movement. Another special challenge for participants was the portrayal of movement within a static model. Sometimes participants portrayed movement in their model without even knowing it. In fact, some of the codes for movement were found when students were viewing other models and inferred movement from them. An example of this is when participants claimed that a certain model would not be able to swim or would only be able to swim to the bottom of the ocean due to the angle of its pelvic fins.

Placement. The subcode of placement dealt with challenges students encountered when placing components of their design onto the body of their model. For example,

when placing a horn on their fish model, Chase and Tyler had to translate and rotate their design feature using three axes in order to place it in a way they desired.

Navigating spatial challenges. Another central code that was directly related to spatial challenges was the navigation of the challenges. When students or participants encountered spatial challenges they navigated them in several different ways. The strategies they chose and which to navigate these challenges depended on the method of modeling. When using the paper drawing method of modeling participants navigated spatial challenges through iterations verbal modeling, gestural modeling, and ignoring. When navigating special challenges during the CAD drawing method of modeling, participants navigated spatial challenges through iterations, receiving assistance, verbal modeling, gestural modeling and omitting. Below we will first provide examples for subcodes that both the paper drawing method and the cad drawing method haven't come, then I will provide examples for the remaining subcodes.

Iterations. Iterations referred to the way a participant or when a participant modifies an existing design. An example of this is when a design feature in CAD is sized to a shape that better suits the modeler's idea for a finished product.

Verbal modeling. When a participant dealt with the special challenge by either writing or orally describing for the model or the spatial aspect of a feature of the model this was categorized as verbal modeling.

Gestural modeling. When a participant dealt with this spatial challenge by pointing, simulating movement with their body in some way, this constituted gestural modeling.

Ignoring. When a participant did not seem to notice or address a spatial challenge in any way, this was categorized as ignoring a special challenge. An example of this is when a participant does not attempt to portray depth when developing a two-dimensional drawing.

Omitting. When a participant encountered a spatial challenge and openly acknowledged that they were not going to address the issue. An example was when Tyler stated, “I am not going to finish the teeth, they take too long.”

Assistance. If a participant asked for or received help in order to solve some sort of spatial challenge this was sub coded as assistance. An example of this is when Greyson asked Tyler how better to align his models pelvic fins.

Spatial Confidence. Pre and post interviews revealed participants’ levels of confidence dealing with spatial tasks. Newcombe, Bandura, and Taylor, (1983) classified several activities as spatial in nature. We believe that confidence in one’s ability to participate in spatial activities must in some way relate to a confidence in one’s spatial abilities. This also relates to developing a model using CAD software. In order to draw a fish to print on a 3D printer, students encounter several spatial challenges; thus, I contend confidence in being able to design a fish using Tinkercad directly relates to confidence in spatial abilities. Several subcodes emerged for this central code: confidence in ability, changes in confidence, confidence in model. Each are explained below:

Confidence in ability. This subcode relates to participants’ expression of confidence or lack of confidence in being able to complete a design task or some sort of spatial task. An example of a phrase that precipitated the development of this subcode is “I would say I am better than most of my friends at building Legos.”

Changes in confidence. During the second interview students were asked explicitly if their confidence and changed in being able to design hey complex figure using CAD software. Also, observations provided a means of triangulation for this data. This subcode was developed to characterize changes and cases confidence.

Confidence in model. During the second interview students were asked explicitly to rate their confidence of their completed 3-D printed model. Also, observation provided a means of triangulation for this data. This subcode was developed to characterize participants' confidence in their model as compared to others in the class.

Model Utility During Argument. During the intervention participants used the forms of models in different ways in order to argue. Through the observation, interviews and exit tickets, participants' thoughts and behaviors regarding model use in argumentation were recorded and analyzed. The central code model utility during argument was developed during axial coding, and under the subcodes participant thoughts and participant behaviors were several more subcodes. These sub codes are explained below:

Participant thoughts. During the first and second interviews the researcher has to explicit questions about students thoughts toward model utility during argument. The questions in the interview protocol dealt with paper drawings and 3-D printed models. Several sub codes emerged from the data analysis: accuracy, perspective, angles, material, generative, and explanatory. These subcodes are explained below:

Accuracy. Several students mentioned the importance of model accuracy in order to best explain or argue in science.

Perspective. The subcode *perspective* dealt with participants' thoughts about the importance of viewing a model from different perspectives.

Material. The subcode *material* dealt with the durability of materials or the use of different materials in order to argue scientifically.

Generative. The subcode *generative* emerged because certain students felt that certain types of models allowed them to generate ideas better than others.

Explanatory. The subcode *explanatory* emerged because certain students Felt that certain types of models allowed him to explain their ideas better than others.

Participant behaviors. The subcode *participant behaviors* deals with the behaviors of participants while day participated and scientific argument with the use of models. Through observation we noted three specific types of behaviors: reference, rotation and gestural movement. The subcodes are explained below:

Reference. The subcode *reference* relates to participants behaviors and which day use the model to reference a certain aspect they were trying to explain.

Rotation. The subcode *rotation* relates to participants behaviors in which they used hey model to rotate the perspective so that others might understand their explanation.

Gestural movement. The subcode *gestural movement* relates to participant behaviors in which they gestured in order to explain something.

Sense of ownership. In the context of a classroom where students are making artifacts, Fortus et al. (2004) mentioned sense of ownership as when someone develops a sense that what they have created is theirs and is directly connected to them. Examples of

statements that precipitated this subcode were “Ours is named magical unicorn fish.” And “My fish has just turned into a boss.”

Strategies for Establishing Trustworthiness

This study established trustworthiness through the four types of triangulation described by Patton (2002): data triangulation, investigator triangulation, theory triangulation and methodological triangulation. As noted in Table 6, many data sources were used to investigate both research questions. This enabled the researcher to corroborate findings from one data source with others. Also, when data was not clear, the researcher was able to contact the participants to better his understanding of the data collected. The use of multiple data sources allowed for the convergence of evidence as described by Yin (2009) and ultimately provided a high level of construct validity.

During analysis, two researchers reviewed and analyzed the interviews of one participant and met with the primary researcher in order to come to consensus on the findings. This process of data analysis allowed for trustworthiness of analysis. The triangulation of theoretical perspectives of model-based argumentation and spatial abilities was evidenced in the literature review and also in the generation of the research questions and taking into account theoretical perspectives during the conclusions of the study. While allowing for emergent themes, this process of returning to other theoretical perspectives assisted in understanding any misconceptions or pitfalls the specific research questions. Both qualitative and quantitative methods were used to investigate each research question, thus methodologies were triangulated as well.

As suggested by Yin (2009) the researcher also constructed a case study database in order to allow for the access of any raw data from the study. Also, a chain of evidence

was developed for each research question. Each finding and conclusion was attached to the correct data source so that the research team or any independent party could trace the conclusions to their respective raw data form. These measures together provided a high-level of credibility and reliability to the findings in this study.

Chapter Summary

This chapter presented the methodology for the study. It described the multiple case study design of the study and the pragmatism philosophy on which it is based. Next, it discussed the role of the researcher and the context of the study as well as described the participants. The data sources, data collection and data analysis strategies were then explained and the codebooks for qualitative analysis were presented. The researcher's efforts to maintain a high level of trustworthiness throughout the study closed out the chapter.

Chapter Four: Results and Conclusions

This study sought to investigate the impact of design based modeling on cases' spatial abilities and argumentation. In order to provide readers with a "vicarious experience" (Creswell, 2013, p.236), I chose to begin this chapter with a rich description of each case's individual personality and their personal interactions or feelings with others in their group. This approach allows the reader to get a feel for the case before delving into the findings; thus, better understanding the context of the study. I then organized findings by research question, illustrating within case patterns and then presenting cross-case comparisons of the findings. Again, the research questions for this study are as follows:

1. How does design-based modeling that involves the design and use of multiple models impact the spatial abilities of middle grade students?
2. How does design-based modeling that involves the design and use of multiple models impact modeling-based argumentation of middle grade students?

Case Overviews

The overviews provided are brief summaries of the cases as they interacted with other participants and the researcher throughout the study. As stated in Chapter 3, this was a rather homogeneous group of participants. All were high achieving white males. Still, personality traits were diverse. Personality traits were gleaned from all data sources, but mostly through interviews with the researchers and observations of interactions with other participants.

Case Overview: Billy

Billy was an exemplary student and seemed to thrive on the fact that most people knew that he was one. For example, Billy's science teacher displayed written inquiries of merit on a bulletin board in the front of the class. This encouraged students to fill out a card with a great science question to post on the board. Out of the twelve posted questions, two were Billy's. This was telling knowing that there are over 50 students that attend this class throughout the day. Furthermore, before the first day of the study, Billy turned in a well-written and well-researched answer to one of the other student's questions: typed and cited. He also enjoyed participating in academic competitions. When discussing his performance in a geography competition, he proudly stated, "I've been to nationals and got the 21st highest score in the country." He was also not shy in divulging confidence in his abilities. "I have excellent spatial reasoning."

It was when he worked with others that he sometimes had difficulty. While working together with Logan, he was slow to compromise on design aspects. In fact, most of the design ideas for the group's first model were his ideas, though contested by his partner. Billy also spent more time actually creating the design on the computer and often told his partner to "wait a minute" when he asked to use the computer. During the design of his second model, both he and his partner decided to work alone. Billy stated he enjoyed this, "because I got to present my ideas the whole time." Deeper more personal issues working with his partner were illustrated in his last interview when he stated, "I think my former partner was trying to convince others that my design was not good." He was noticeably and personally hurt by this and continued to defend his design to me during the interview. In summary, Billy was highly confident in his intelligence, but had

a hard time compromising with others on shared work. He was also personally sensitive to critique.

Case Overview: Chase

During his first interview I often repeated questions to Chase because the time he took to answer made me think he did not hear or understand the question. It quickly became apparent that he was thinking thoroughly to obtain and present his best answer to the question. Chase seemed very interested in the competition inherent in scientific argument. Many times he seemed more interested in others' designs than he was with his own. He also appeared to really enjoy the act of argument using reasoning. During his small group discussion, he often challenged others by using theory and reasoning to justify his own claims.

For the most part Chase worked well with his group, but he did put forth a condescending bend when he critiqued or defended his ideas to others. "What do you think it would do?" he remarked in a defensive tone after someone asked how his fish would react if something was attacking it. He usually followed this with a slight giggle that would lighten the tone of the dispute, but it seemed to have a detrimental effect on the safety people felt to criticize his design.

Case Overview: Garrett

Garrett described himself first as a LaCrosse player. "Yes, I am better than most of my friends at LaCrosse. I practice all the time." In every respect he seemed to be the athlete of the group. He was extremely polite and thanked me after every interview and lesson offering a handshake. During his first interview, he was proud to mention that he would rather play outside than play video games. Out of the group he seemed the least

eager to spend the time to participate in a modeling activity rather than fraternize with his friends. Although he was quiet within the context of the study, he appeared very talkative and popular with others outside of the group.

Garrett worked with Preston on both of the models he created. Although he worked well with Preston and offered ideas, he seemed to take a secondary role in most respects. During the first design, Garrett allowed his partner to complete the majority of the design and only began designing on the computer when I encouraged him to try the Tinkercad program. Also, he was the least involved member during structured discussion.

Case Overview: Greyson

Greyson was a very quiet, yet participatory student. During interviews he seemed calm, but uninterested in describing any of his ideas in great detail. He enjoyed cross country running and other sports. He also enjoyed playing video games involving creative design and construction of imaginary worlds and stated, "I like challenges."

From the beginning of the intervention he seemed very quiet and somewhat withdrawn. When placed in a group, he scooted his chair farther away from the other two in his group and ended up working alone most of the time. It is important to note that he did speak to and get along well with everyone in the group. In fact, he was observed laughing about his own design issues or asking questions of his partners.

Case Overview: Logan

Logan was an extraordinary student. During the time of the study the school newspaper recognized him for placing in a regional math contest, and winning first place in a science essay contest. His vocabulary was noticeably advanced for his age. He enjoyed building things and seemed passionate about inventing. "I am really interested in

artificial intelligence. I am learning a lot about the brain and trying to put what I am learning into code.” He also addressed me as sir and offered a handshake after every interview.

Logan had a difficult time working with his partner, Billy. During his second interview, Logan quietly said, “Billy is kind of a hard person to work with. I don’t think I would have had problems working with anyone else.” This was Logan’s reasoning for working on his own for his second design. Logan did seem to get along well with the rest of the participants and was observed talking and laughing often with them.

Case Overview: Preston

Throughout the intervention Preston seemed a very happy and willing participant. He was often the first one to raise his hand to offer an answer, and was one of the more participatory members during whole class discussion. He mentioned his love and talent for sailing during an interview and also mentioned that he played soccer. During the design component of the intervention, Preston was very focused, but sometimes was less serious than others about his final product. He was observed a few times speaking about creative, yet not at all plausible design ideas. It seemed he was offering these ideas to get attention rather than as component he seriously intended to add to the model.

Preston worked well with his partner, Declan. Although he tended to lead the work, he offered Declan many opportunities to design and discuss ideas about the model. In the end, Preston’s open encouragement for Declan to help with design seemed to persuade Declan to assist more than he did at the beginning of the intervention.

Case Overview: Tyler

Tyler was a builder. He mentioned that he builds with Lego's almost every day and he especially liked "to build useful things." Not only did he build with Legos, but he discussed how he built a gladiator helmet using duct tape and cardboard, an intricate flower using paper and sticks, and described his affinity for the construction-simulation video game Minecraft. He was also one of the loudest participants. His voice was often heard above all others, yet he did not seem to notice.

Tyler and Chase often disagreed on design components of their model, and while neither gave in completely, it seemed that Tyler was more open to new ideas than Chase. Their arguments were respectful and many times they would laugh and smile during their discussions. He also seemed to enjoy talking with and helping Greyson with Tinkercad. Greyson often asked Tyler how to manipulate something on his computer and Tyler obliged with a smile. More than any other participant, during argument Tyler was able to criticize what he believed to be flawed design components with questions instead of blatant statements. For example, Tyler asked, "Do you think that drag will be a problem with the backwards dorsal fin?" instead of merely explaining that he believed the dorsal fin would negatively impact the fish's navigation through the water. This seemed to elicit a more thoughtful rebuttal from participants than the more common defensive rebuttals when other participants critiqued.

RQ 1: Impact on Spatial Abilities

This section first presents findings from the pre and post intervention interviews that describe participants' prior spatial experiences and their confidence and interest in such tasks. I then present findings involving quantitative data gathered from the MRT (Vandenberg, Kuse, & Vogler, 1985) the RPSVT:R (Yoon, 2011) spatial abilities

instruments. Next, from content analysis of CAD drawings and observations, I present findings involving how and what design tools participants used to complete their CAD drawings. From qualitative data I will present themes and subcategories what types of spatial challenges participants encountered during design-based modeling and how they navigated such challenges. Finally, a summary will end the section.

Confidence in Spatial Tasks

Confidence in ability. Newcombe, Bandura, and Taylor (1983) consider certain activities outside of the school environment to involve spatial tasks. During the preinterview I asked all participants what types of activities they most enjoyed. In the following section I present these activities and also the confidence level revealed about performance on those tasks.

Chase, Garrett, Greyson and Preston all named sports: soccer, Lacrosse, cross-country running and sailing respectively as their favorite activity. Each of the participants who mentioned sports ranked themselves as one of the top players on their team. Chase stated that he excelled at soccer “because I understand where to be at the right time.” This idea of positioning on the field is one spatial task involved in soccer.

Logan and Tyler expressed that they enjoyed building things using Legos. Tyler enjoyed building medieval castles and stated he would “probably be better than most of his class” at this type of building, while Logan enjoyed building “mechanical things” using Lego robotics and could do better than most people in his class. Logan was the only participant who had prior experience using design software other than what we use during this intervention.

Several participants mentioned that they played videogames that dealt with either building in 3D space, navigating through 3D space while using maps or coordinates, or puzzle making. In respect to their personal performance on the video games they mentioned, Chase, Billy, and Tyler ranked their performance level as higher than most people they knew. Billy stated that in his favorite game he is, "One of the most powerful people in the world."

Each of the sports, building activities, and videogames that the participants mentioned are considered to involve spatial tasks (Newcombe, Bandura, & Taylor, 1983).

In summary, all participants in this study had an interest in activities outside of school that involved spatial tasks. Furthermore, the students expressed a high level of confidence about performance on these types of activities.

Changes in spatial confidence. During the pre and post interviews we asked participants how confident they were about being able to design a fish using Tinkercad. All participants had previously used this program for a brief amount of time, and we felt that they could gauge their answers using their prior knowledge of the program. Making a fish on Tinkercad involves tapping into their spatial abilities and so I developed the question to be related to their confidence in designing an object using Tinkercad. Before the intervention, all participants except for Billy stated that they were confident that they could create the fish. Billy stated he was highly confident that he could create the fish. He added, "I have excellent spatial reasoning."

All participants except for Greyson expressed a higher level of confidence that they would be able to make the same fish after the intervention. Although Billy first stated that he was highly confident, during his second interview he stated he was even

more confident than he was before the lesson. Greyson stated that he was just as confident as he was before the intervention. Other participants explained their reasoning behind their increased confidence which seemed to fall into two categories: learning about design tools and practice with the software. Chase and Logan's explanation for increased confidence involved learning about design tools. For example, Chase explained that he had an increased confidence that he would be able to create the fish.

Well, the problem (before intervention) was not that I wouldn't be able to visualize it with the general shapes, it was really, it was if you didn't have a custom shape to add in these teeth it would have been ridiculous. (Chase, second interview)

Learning how to use the custom shape designs allowed him to feel more confident in being able to design the fish. Logan also seemed to have learned more about the design tools. "I know now that the teeth would take some experimenting (Logan, Second Interview)." Billy, Garrett, Greyson and Tyler explained that practice with the Tinkercad program helped them increase their confidence. Billy stated, "As you keep working on it, you get better at it. It took some practice to figure how to angle it to see exactly what I wanted (Second Interview)."

Confidence in Model. It was interesting that although some participants' models were highly criticized, all believed that their models were comparable to or better than other participants' models. Billy's model, in particular, was highly criticized, but he defended his design fervently during the structured argument, and throughout the second interview. "It was unfortunate that certain glitches in the 3D printer prevented it from completely printing correctly, but I feel that my design was very plausible (Second

interview).” It is important to note that the 3D printed design was extremely similar to the CAD drawing. Two researchers looked over Billy’s CAD drawing and its respective 3D printed model and could not find the inaccuracies that Billy described.

All participants stated that their models were either comparable or among the top designs, yet all except for Chase believed they needed to change certain components of their designs. At the end of the structured discussion, participants voted Chase and Tyler’s design the most plausible of the models. Chase’s ideas were mainly the ones that went into the design. This may be why Chase believed the design needed no changes. Chase stated that his design “Worked very well considering the environment and it had adaptations that you see in nature today.”

Besides Chase, all other participants believed their designs needed changes after intervention. In these cases, their proposed changes were inspired by structured discussion. For example, Logan wanted to, “Make the side fins slightly longer (exit ticket).” Although he stated on his exit ticket this was because “seeing other models” made him want to “make the fish have more stability,” (exit ticket) Billy had openly criticized Logan’s fin design for being too small during the structured whole-group discussion. Logan provided a rebuttal for Billy’s criticism, but later decided he needed larger fins. In his second interview, he conceded that Billy’s mention of his fins was the first time he thought about changing them. Greyson was more direct in stating, “People in the discussion said that it needed teeth (exit ticket).” Although Tyler’s model was voted most plausible, he still believed it needed some work on the mouth. This illustrated that there still was not complete consensus between Tyler and Chase on their model.

After intervention all participants felt that modeling using Tinkercad and a 3D printer would be something they would like to do more in science class. Tyler claimed it would help him to, “understand things better. It would make things clearer.” Billy stated, “I think I would be really interested in doing it more. It was fun.”

In summary, participants were generally confident in their ability to construct a CAD drawing before intervention, yet their confidence grew after the intervention due to practice with the program and / or learning about new design tools. Participants ranked their design highly as compared to others, but most still felt a desire to change their design due to discussion and viewing and comparing their model’s design components to other participant-designed models. Overall, participants expressed a desire to take part in design-based modeling in the future.

Spatial Abilities

This study employed the use of two quantitative measures to ascertain spatial abilities of participants before and after intervention. This subsection will first present findings related to the MRT pre and posttest and then present findings related to participants’ performance on the RPSVT:R. I will then present findings across both tests to show any changes in performance levels across participants.

Mental rotations test. I administered the MRT pretest to all cases three days before the intervention and then administered the posttest two weeks after the intervention. In all cases except for one, participants increased their score on the posttest relative to their pretest scores. Pretest scores were particularly high as compared to other studies using the MRT. In fact, all of the scores are relatively high compared to studies involving older participants. In a study involving college students, (Vorstenbosch et al.,

2013) first year medical students scored a mean of 14.40 while the average scores for the seventh graders in this study measured 14.29 (Vorstenbosch et al., 2013). For this reason, it can be inferred that these seventh grade students have relatively high spatial ability for their age. Still, there was a wide range of variance in scores. The range of scores was 9 while the test only had 20 questions.

As detailed by Table 9, Chase and Logan scored the highest on the pretest and also had the smallest increases from pre to post. This may indicate a ceiling effect for these particular students on this particular test. In fact, when reviewing other studies' reported mean gains for students close to this age on this test, the same mean gains are not possible with these participants' pretest scores. For example, Erkoc, Gecu, & Erkoc (2013) reported an eight point gain from pretest to posttest mean scores for eighth grade participants. In this study an eight-point mean gain would not be impossible. The participants' mean gain in this study was a 2.29 points while the pretest mean was nine points above the aforementioned study.

Cross-case comparisons are illustrated in Figure 6. Logan's score from pretest to posttest did not change, while Garrett, Greyson and Preston scored the lowest on the pretests and registered the largest gains from pretest to posttest. Therefore, the two highest pretest scores changed the least while the three lowest pretest scores showed the largest gains from pre to posttest.

Table 9.

MRT Scores

	MRT	MRT	MRT	MRT
Participant	Pretest	Pretest %	Posttest	Posttest %
Billy	17	85%	19	95%
Chase	19	95%	20	100%
Garrett	14	70%	18	90%
Greyson	10	50%	14	70%
Logan	18	90%	18	90%
Preston	8	40%	11	55%
Tyler	14	70%	16	80%
Mean	14.29	71%	16.57	83%

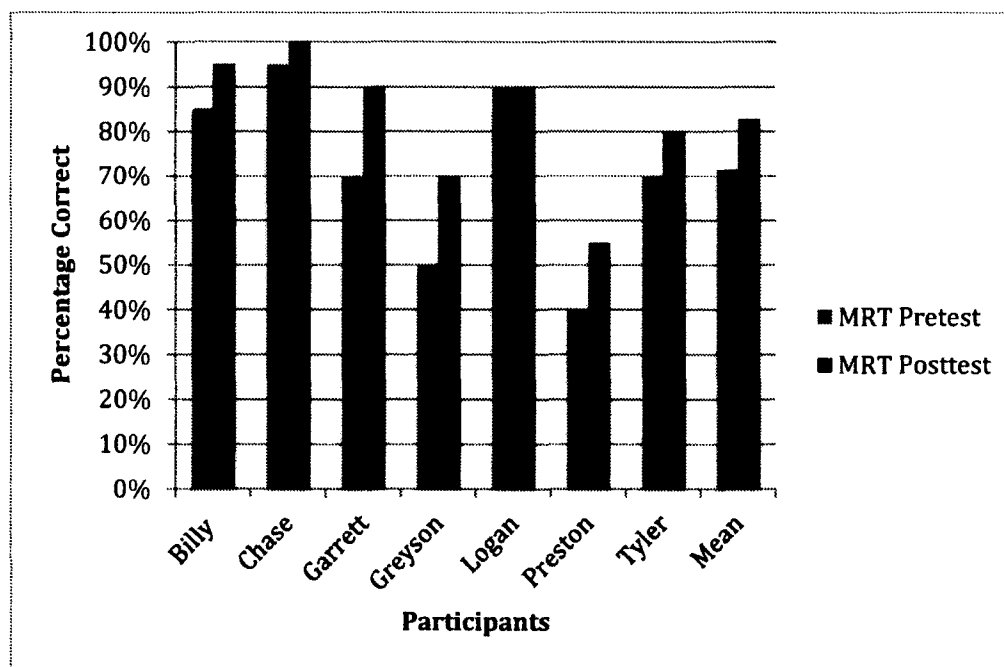


Figure 6. Pre and Post MRT scores of participants.

Revised Purdue Spatial Visualization Test: Rotations. After participants completed the MRT they had a five minute break, and then they began the RPSVT:R. The test consists of 30 multiple-choice questions. After reviewing findings from other studies using this instrument, it seems that our participants scored well for their age on this test compared to others. For example, participants in this study scored an average of 66% on the pretest while middle and secondary geometry preservice teachers enrolled at a major research university participants averaged a 65% (Unal, Jakubowski & Corey, 2009). This is similar to the findings we had on the MRT that indicated these participants have a high spatial ability for their relative ages. For studies using the MRT and the PSVT:R or the RPSVT:R with students of similar ages, I found no mean pretest scores as high as our participants'.

Table 10.

RPSVT:R Scores

	PSVT:R	Percentage	PSVT:R	Percentage
Student	Pretest	Correct	Posttest	Correct
Billy	19	63%	25	83%
Chase	20	67%	22	73%
Garrett	19	63%	24	80%
Greyson	19	63%	21	70%
Logan	25	83%	23	77%
Preston	17	57%	21	70%
Tyler	20	67%	23	77%
Mean	19.86	66%	22.71	76%

Referenced in Table 10, Logan again scored highly on the pretest while Preston again recorded the lowest pretest score. Logan was the only participant that did not increase his score on the posttest. When analyzing the posttest, it was interesting that Logan marked the first five answers on the RPSVT:R incorrectly. This was different than his performance on the pretest, where incorrect answers began in the middle of the test and most were near the end. In this form of the test, the questions increase in difficulty (Yoon, 2011) which means that Logan was able to answer the most difficult questions correctly but answered the easier questions incorrectly. When asked about his performance on the test, Logan said, “I don’t remember having any problems.” All other participants increased their scores on the posttest. Billy in particular answered six more questions correctly on his posttest and increased his score by 20% from pretest to posttest.

Composite Scores. To record a composite score for each participant, I calculated the average percent correct for each participant for both the MRT and the RPSVT:R. The pre to post comparisons are presented in Figure 7. All but one participant recorded a gain from pre to posttest with a mean gain of 10% for all participants. Five out of the seven participants recorded a gain of 10% or higher. The two participants that recorded the highest pretest scores were the two participants that recorded small or no gains. Again, this may be due to a ceiling effect.

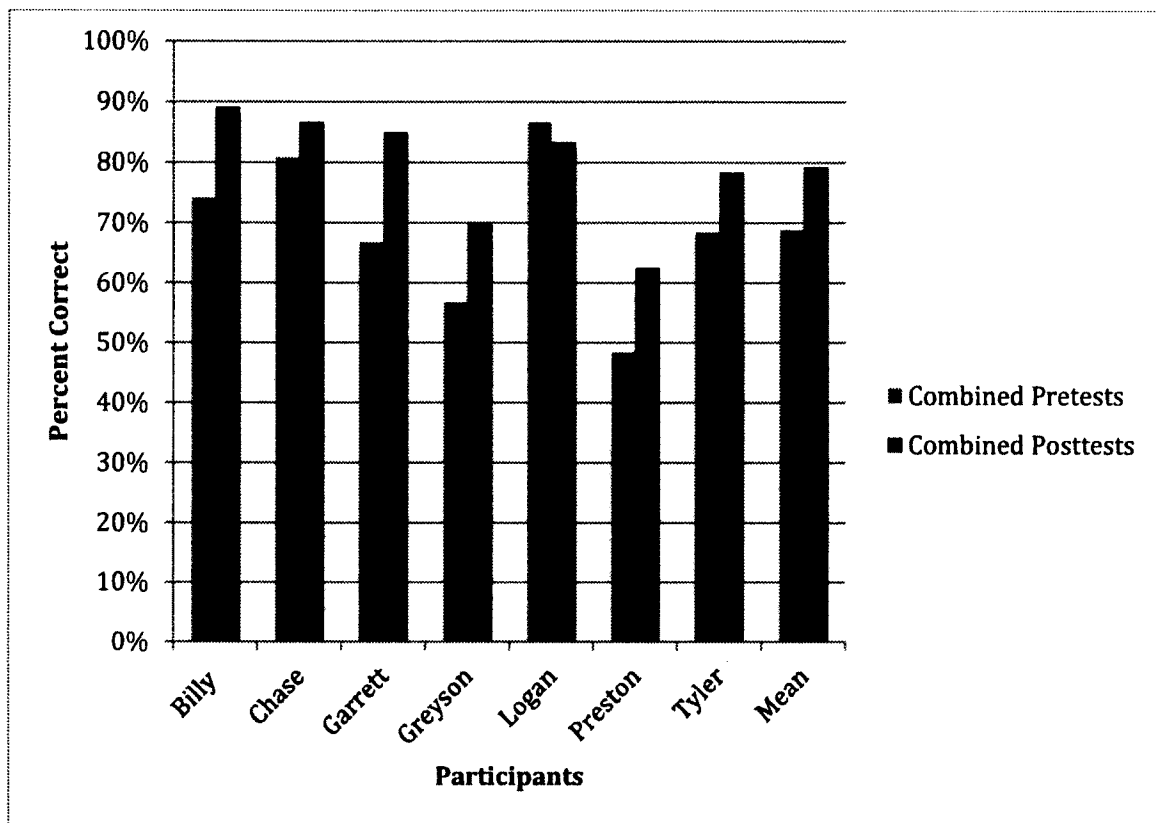


Figure 7. Composite spatial abilities scores.

The findings on spatial abilities revealed that participants in this study entered the intervention with relatively high spatial abilities. The relative confidence and their performance on spatial tasks and their prior spatial experiences may have been a factor related to their high level of performance on these tests. Such a conclusion is in agreement with other studies that have found positive correlations between childhood spatial experiences and spatial performance (Doyle, Voyer, & Cherney, 2012; Newcombe, Bandura, and Taylor, 1983).

Although in this study there are a small number of participants and we cannot claim significance or generalizability, a mean gain of 10% on these spatial abilities tests is interesting. It is also promising that all but one participant increased their score after

intervention. In a larger study with college students, Martin-Dorta, Saorin, and Contero (2008) found spatial abilities to be increased rather quickly when using CAD software.

Tools Used on CAD Software

In order to investigate the tools students used, we performed content analysis on each CAD drawing in order to better understand the tools used to create each one. We also used the video observations and the interviews to triangulate these findings and to add to the description of how tools were used. All participants were allotted approximately 15 minutes to work on Tinkercad for the first design and then 35 minutes to work on Tinkercad for the second design. Tinkercad provides users visualization tools in order to change perspectives of the workspace and also design tools in order to create their design. During both design one and design two, all participants were constantly using their visualization tools to manipulate the perspective on their design. The visualizations tools allow users to either rotate around their design in order to see it any angle out of 360 degrees or to zoom in and out to better view the various sized components of their design. Compared to the number of visualization tools, there are many more design tools that participants can use. Some participants chose not to use certain design tools or relied on certain design tools more heavily. Table 11 and Table 12 below illustrate what tools participants used for each CAD drawing. This is presented to provide a general overview of the types of tools each of the cases used.

Table 11.

Design tools used on first CAD drawing

	Billy &	Garrett &	Chase &	
Design Tools	Logan	Preston	Greyson	Tyler
simple shape		1	1	1
extrusion	1	1	1	1
Community				
size	1	1	1	1
x-axis				
translation	1	1	1	1
y-axis				
translation	1	1	1	1
z-axis				
translation	1	1	1	1
x-axis rotation	1	1		
y-axis rotation		1		
z-axis rotation		1		
hole			1	
align				
Total	6	9	7	6

Table 12.

Design tools used on second CAD drawing

Design Tools	Garrett &				Chase &
	Billy	Logan	Preston	Greyson	Tyler
simple shape	1	1	1	1	1
extrusion	1	1	1	1	1
Community		1			
size	1	1	1	1	1
x-axis					
translation	1	1	1	1	1
y-axis					
translation	1	1	1	1	1
z-axis					
translation	1	1	1	1	1
x-axis rotation	1	1	1	1	1
y-axis rotation	1	1	1	1	1
z-axis rotation	1	1	1	1	
hole	1	1		1	1
align		1	1	1	1
Total	10	12	10	11	10

Participants used more tools during the second design. During the second design, participants were allotted more time and also were more familiar with the software. It

was apparent that tools like the alignment tool were not as needed during the first design period because most participants were quickly adding components to the design without taking the time to align them perfectly. It was interesting that all participants were able to complete the first design to print in 15 minutes.

How participants used CAD tools. Certain participants seemed to rely on particular tools more than others. Billy, for example, spent most of his time manipulating the extrusion tool to make unique shapes. This was most apparent during the second design when he chose to work on his own. During his second interview Billy expressed why he enjoyed using the extrusion tool. “It allowed me the greatest degree of creativity. With an actual mold to mold substances you can make artificial things that are only present in nature.” In fact, the extrusion tool was one of the easiest ways to create custom curves, which in this case appeared more realistic on the design of a fish.

Some of the tools allowed for participants to obtain symmetry and balance that they seemed to desire in their designs: design aspects that were often critiqued during structured discussion and will be discussed later in this chapter. Preston commented on the use of the alignment tool during the structured discussion. “At first I couldn’t get the eyes to look right, but then using align helped me to make them look symmetrical. That made it better.” This was an important find for Preston and Garrett because during his first design session they were having great difficulty aligning the eyes of his CAD drawings as they painstakingly toggled through visualization tools and the different rotation and translation tools in order to make their design more symmetrical. In Figure 8 it is evident that the eyes of the fish are angled similarly, making that design feature seem

asymmetrical. Their second CAD drawing (Figure 9) is more symmetrical having created a reflection of the other side.

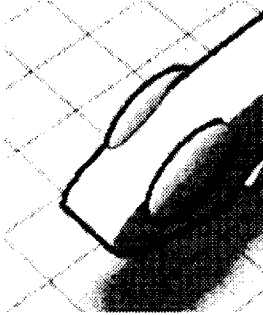


Figure 8. Preston and Garrett's first CAD drawing

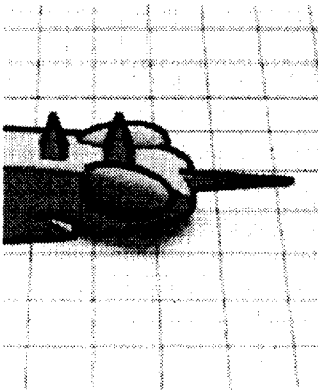


Figure 9. Preston and Garrett's second CAD drawing

Chase also commented on the use of the alignment tool during structured discussion when offering advice to another participant. "A solution to that problem is to copy, paste, rotate and align." This illustrated a common software tool that was not included in Table 11 and Table 12. Copying and pasting a single design component allowed participants to create many similar design components in order to increase the symmetry and balance of their designs.

When analyzing observation data, it was evident that certain tools involved the participants in spatial rotation more than others. All rotation tools and visualization tools allowed students to rotate either their perspective or the actual design in space. It could be argued that providing them access to this software essentially provides them a rich spatial experience that could ultimately build their spatial abilities.

As mentioned in the literature review, transformational reasoning is important for STEM subjects as well. The extrusion tool allows for manipulations of a 2D circle to transform a 3D cylinder in real time. Observations of participants using this tool revealed that participants would alter one design component several times in order to create just the right design. For example, in less than four minutes using the extrusion tool, Billy made 18 different manipulations to one design component. These quick iterations transform a 2D figure into a 3D design component again and again so that the participant immediately sees the transformation as a 3D figure. This is different from programs like Google Sketchup where users construct 3D figures using several 2D figures. In fact, Tinkercad involves only 3D figures on the workplane itself: 2D construction figures cannot be brought into the workspace.

The findings presented in this section describe what tools participants used and when and how they used them to design their model. Although all participants used most tools, some participants professed certain tools as more helpful for specific tasks. All participants were involved in spatial manipulations in a virtual 3D space. The extrusion tool allowed real time visualization of 2D and 3D objects which also allowed participants to visually manipulate a 2D circle into a customized shape and then transform it into 3D

objects. In the next section, findings will describe how both paper drawings and CAD drawings elicited spatial challenges.

Spatial Challenges and Their Navigation

Observations, exit tickets, interviews and artifacts revealed two major themes related to participants' use of spatial reasoning: spatial challenges involved in design-based modeling and participants' navigation of these spatial challenges. The researcher facilitated two methods of model design in which all participants engaged: paper drawings and CAD drawings (later resulting in a 3D printed model). Subcategories of each theme are explained below and are separated by design method. I structured this section to highlight the spatial difficulties participants encountered and navigated so that they could be compared for each method of design. After presentation of the themes and subcategories, I summarize by presenting a comparison of the findings from each method of design-based modeling.

Spatial challenges. One of the most obvious differences between the two methods of design was that the paper drawing involved navigating a 2D environment while the CAD drawing involved navigating a virtual 3D environment. All completed paper drawings were a single 2D profile representation of a participant-designed fish while completed CAD drawings were a 3D representation of a participant-designed fish. Several subcategories emerged as types of spatial challenges for participants regardless of the method: manipulating perspectives, proportion, depth, symmetry, balance, placement, and movement. Below, I present each subcategory first in the context of the paper drawings and then in the context of CAD drawings.

Manipulating Perspectives (Paper Drawing). While participants designed their paper drawings, it is assumed that they manipulated their conceptual understandings of the fish design in their mind while they drew their representation on paper. Video observation did not reveal any rotation of their paper in order to view their design from a different perspective. In Chase's second drawing, he created an inset drawing of a zoomed in version of the compound eye. This helped him portray the vast amount of lenses he intended.

Manipulating perspectives (CAD drawing). In order for participants to design certain aspects of their fish using CAD software, it was necessary to change the perspective, or the participant's angle of view, in order to complete their design. Participants could do this with the visualization tools in Tinkercad. For example, when viewing one side of the fish drawing on CAD, it is extremely difficult, nearly impossible to design the other side of the fish without manipulating the perspective. The same goes when trying to add design features to the underside of the fish when viewing it from above. In this way, participants were presented with the spatial challenge of manipulating the perspective.

Manipulating the perspective was also important when a participant "lost" a design component. This occurred when a participant brought in an object and accidentally placed it behind their model and out of view. For example, Garrett stated, "It disappeared! What?" Immediately he rotated his perspective and was able to see the pyramid that he brought onto the workplane. "Oh, there you are!" While Greyson was trying to put teeth into the mouth of his shark, he slid a pyramid shaped tooth all the way into the fish's body and it appeared to vanish. In order to find it, Greyson moved fish

body and the pyramid was uncovered. By changing the place of the body within the virtual 3D environment, the perspective was changed.

Proportion (paper drawing). Billy, Greyson and Chase's paper drawings and their discussions revealed spatial challenges that dealt with proportion. For example, Billy's drawing involved three erasures dealing with the size of the pelvic fin. When asked about it during the intervention, he stated, "I couldn't get it to exactly match the fish." Though other components of design seemed to be ill-proportioned, there seemed to be no discussion or notice of the issues.

Proportion (CAD drawing / 3D print). During the development of the CAD drawings, proportion was a common spatial challenge. All available shapes that are imported to the workplane are a standard size, which means very seldom would they be proportionate to the participants' design until there is some sort of manipulation. This means that every component that is added to the fish involves spatial manipulation dealing with proportion. Smaller aspects of design were a particularly difficult challenge for participants. For example, Garrett spent over nine minutes attempting to add teeth to his CAD drawing, yet he was not able to find a proportion that would suit his approval. He abandoned the design feature in order to finish another part of the design. Billy commented on the ill-proportioned pelvic fins on Logan's final 3D printed model. This was an aspect of his design that Logan stated that he would like to redesign on his exit ticket and during his last interview.

Depth (paper drawing). During Garrett's first drawing, he wanted to show hair-like structures that covered the body. In order to do this, he drew small lines that circled the fish's perimeter. Later he stated, "I didn't know how to show that in the drawing. It

would have just looked colored if I drew them all in.” Tyler, Chase, Garrett, Greyson and Preston all drew circular eyes on their paper that they later explained as bulging away from the body, but none of them were able to or tried to represent the depth on their paper drawings to show that the eyes would bulge. Only Billy, Garrett and Preston attempted to represent depth in their drawings, and they did so with the pelvic fin. In order to do this they overlapped the pelvic fin onto the body of the fish so that it appeared to emanate from the side of the body instead of the bottom. Though Tyler drew his pelvic fin as originating from the bottom of the fish on paper, his CAD drawing showed it originating from the side of the fish.

Depth (CAD drawing). Using CAD allowed participants to view their drawing in a virtual 3D space. On their CAD drawing all participants chose to add design components that displayed a certain depth. One example of depth that all participants used in their design were pelvic fins that angled out of the sides of the fish design. Another example was the bulging eyes of Garrett and Preston’s CAD drawing. Garrett and Preston decided to make the eyes to better represent shape of the compound eyes. Spatial challenges of depth were not only protuberances: they also included depressions. For example, Logan and Greyson designed holes in their CAD drawings to represent filters for the mouth of the fish. A unique component of Tinkercad is that all of its design pieces are 3D objects, which means they all involve some depth; thus, all aspects of design involved depth.

Symmetry (paper drawing). After analysis of the drawings it seems that all participants created their paper drawings with the notion that the unseen side of the model would be a reflection of the one they drew. Besides Garrett, all participants chose not to

draw components that may be construed as originating from the unseen side of the fish. When asked why their model only had one eye, Chase and Tyler first looked confused, and then Tyler answered, “Oh, I get it. It’s on the other side. You can’t see it, but it’s there.” Garrett chose to draw two pelvic fins and one was drawn so that it seemed to originate from the unseen side of the fish. Still, he was not able to place the second pelvic fin so that the angle would appear symmetrical, but no other participant appeared to notice.

Symmetry. All participants attempted to show symmetry in some way with their CAD drawing. This was most evident with the placement of the eyes and pelvic fins, as all but Billy’s CAD drawing illustrated nearly perfect symmetry. Billy’s CAD drawing is one that can illustrate spatial challenges that involved symmetry. As you can see in Figure 5, Billy’s dorsal fin is slightly off to the left. Another issue is the placement of the pelvic fins: the right pelvic fin is slightly closer to the nose of the fish than the left pelvic fin. Also, the angle of the pelvic fins are not the same on two different axes. This example illustrates that when a participant desires to create a design with symmetry, as Billy attempted to do, they are challenged to manipulate 3D objects in space on three different axes and place them in a symmetrical fashion respective to their whole design. These asymmetrical aspects of Billy’s design were highly criticized during the structured whole group discussion.

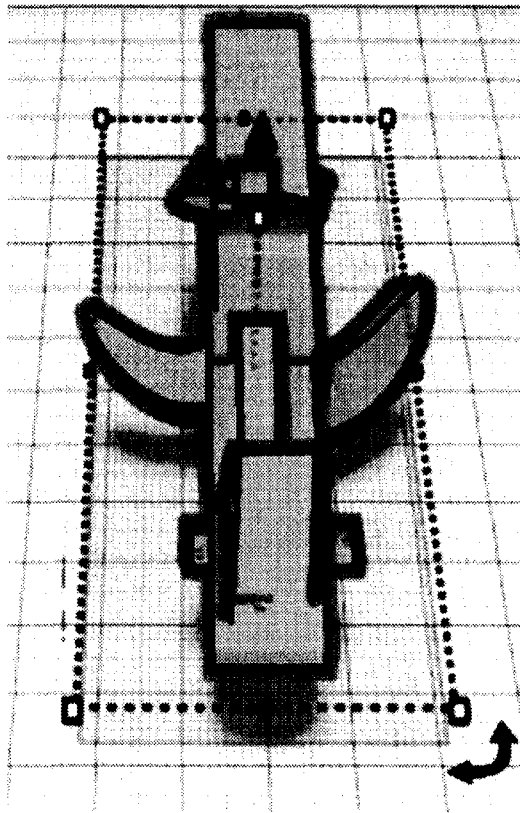


Figure 10. Billy's second CAD drawing (top view).

Balance (paper drawing). Tyler had difficulty with establishing appropriate balance during his drawing. Apparently he was upset about the size difference between the head of his fish and the body. This made the fish drawing similar to that of a whale. Laughing, he told his small group, "Mine looks like a whale!" and then said, "I can't draw."

Balance (CAD drawing). Billy's CAD drawing in Figure 10 illustrates spatial challenges related to balance. In this design while there is little complexity to the front of the fish, there seems to be a great amount of design features at the tail. The design does not illustrate proper balance. During the first structured whole-group discussion, many participants critiqued the great size of the caudal fin of Billy and Logan's first 3D print.

In Figure 11 the caudal fin is smaller than that of their first design, yet the other features of the design make it seem unbalanced again.

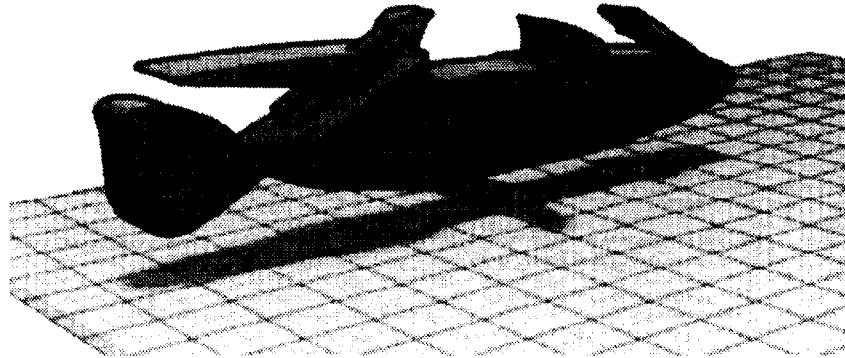


Figure 11. Billy's second CAD drawing (profile)

Movement (paper drawing). Only two participants chose to represent movement through their paper drawings. Chase drew arrows to show that the mouth of his fish would open in two different ways and Tyler drew an arrow to show that over time the eye of his fish moved toward the top of the body. For the most part, although most mechanical abilities of the fish were not displayed in the drawings, participants spent a lot of time speaking of how their fish would move and maneuver.

Movement (CAD drawing). Even more so than the paper drawings, movement was not overtly displayed on the CAD drawings. Through the placement of design components in the CAD drawing though, thought experiments could imply movement. For example, note the angle of the pelvic fins in Figure 6. During participants' argument involving the 3D model printed from the CAD drawing illustrated in Figure 6, Logan claimed that the fish would swim "right into the ground," and Chase said it "would never be able to swim unless it had a swim bladder the size of Texas." Logan and Chase were able to infer movement from the angle of the pelvic fins. Billy, on the other hand, argued

that he placed the fins that way in order to show that they could move in different ways in order to uncover prey in the sand. Hence, Billy's placement of the pelvic fins did not imply the movement he intended.

Placement (paper drawing). While creating a paper drawing of a fish, participants must place design components in specific places that match their personal conceptions of the structural design of the fish. Observations did not reveal particular instances of participants having difficulty with specific placement of their design components except when the placement dealt with symmetry or balance.

Placement (CAD drawing). Simply placing design features onto the body of the CAD drawing involved several spatial challenges. For example, note the fin encircled in Figure 12. After shaping and sizing the fin, Greyson translated the shape across the virtual 3D space toward the fish body. In this case, Greyson translated the shape on three different axes and then rotated it on one axis in order to place it on the fish. During this process, Greyson used the visualization tools to manipulate the perspective in order to make sure that the fin was placed correctly onto the fish. Not counting the shaping or the sizing of the fin, for Greyson, the process of placing the fin involved a total of 23 movements or clicks of the mouse (observation).

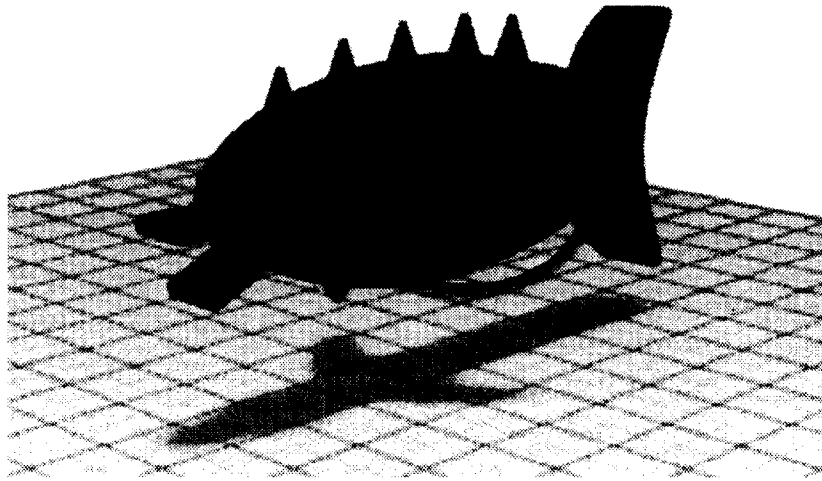


Figure 12. Greyson's second CAD drawing (fin focus)

He then asked assistance from Tyler. Tyler ended up moving the body of the fish to reveal the missing pyramid. In this example, the perspective was manipulated by moving aspects of the design.

Navigating spatial challenges (paper drawings). Results showed that participants navigated spatial challenges during the development of their paper drawing in four ways: paper drawing iterations, verbal modeling, gestural modeling, and CAD modeling. These subcategories differed from how participants navigated spatial challenges when developing their CAD drawings. For that reason, I first present how students navigated spatial challenges during their paper drawing.

Paper drawing iterations. Most iterations of design components for the paper drawings lasted a brief amount of time. In fact, the only erasures on paper drawings were on Billy's (three erasures) and Greyson's (one erasure) paper drawings. These iterations occurred on the first paper drawing. There were no visible iterations to any of the second paper drawings. For the most part, participants' first attempt at drawing their fish on paper was the final attempt.

Verbal modeling. Verbal modeling was very common during both the development of the paper drawing and the discussion of the drawings in small groups. During the development of the paper drawing, most participants (Billy, Garrett, Chase, Tyler, Greyson) tended to label components that they had trouble drawing. In this case verbal modeling was in the form of writing. For example, Billy drew several circles and then labeled them as a compound eye. This may have helped others to understand that he intended for the eye to bulge away from the fish. Similarly, Garrett drew a checkerboard pattern inside a circle to represent an eye and then labeled it a compound eye. Chase labeled the mouth on his model with the word “hinged” because he “didn’t want to try to draw the inside of the fish (observation).” In all of these cases, spatial attributes of design were better understood with labeling.

During the small group discussion and in a few cases during the first gallery walk, spatial design components were verbally modeled in detail that were not well-represented in the drawings. For example, during the gallery walk, Chase asked Preston about the “force field” encircling his fish. Preston explained that it was not a force field and that they were “hairs that cover the entire body of the fish. It helps it sense things around it.” Billy explained his paper drawing to Logan saying, “They are more like cones, not really triangles.”

Gestural Modeling. Gestural modeling in this study only occurred simultaneously with the use of verbal modeling. In the simplest form, gestural modeling occurred as a participant pointed to direct attention to a specific aspect of their paper drawing during explanations or argument. This happened often during the small group discussion when

participants were presenting and explaining their model to others in their group but also happened when in the middle of developing their fish model.

Gestural modeling often dealt with movement of the fish or a mechanical aspect of the design. Movement was something that most drawings did not illustrate. During the explanation of Chase's mouth design, he moved one hand like a closing mouth, lifted in a shovel like fashion and stated, "The mouth would move like this to shovel up the sand and prey." Similarly, Billy tried to help his partner understand the reason for his fish's paddle-like pelvic fins by flapping his arms and stating, "The fish scatters the sand with its fins. This uncovers the prey."

Ignoring. Many participants simply chose to leave certain aspects of design to the CAD drawings. As mentioned earlier, drawing more than one side of the fish did not seem to cross any of the participants' minds as an option or as a needed detail for the development of their paper drawing. Only completing one side of the fish in a CAD drawing simply did not happen. At some point during the first drawing, three (Greyson, Chase, Tyler) of the seven participants decided to halt attempts to draw a certain design component on their paper while expressing their poor drawing skills. For example, while Greyson was drawing, he showed his paper to Chase. Chase asked, "Is that a frog's head?" To that, Greyson smiled and said, "No, but I am not changing it. I am so bad at art." The candor during these conversations was light and playful, but it seemed that nearly all participants were somewhat self-conscious of their drawing ability, and many aspects of design were first represented on the CAD drawing.

Some participants chose not to complete a second paper drawing, though they were allotted time to do so. Greyson, Logan, and Chase chose not to draw a second paper

drawing before the development of their second CAD drawing. Greyson, Logan, Chase, and Billy stated in their second interview that the CAD drawing was easier in some way. Logan explained in his second interview, “The first one helped me get my ideas down, but I didn’t need to draw the second one because I can do it on the computer just as easy.” Greyson stated in his second interview, “It is easier for me to use the computer,” and then in a more humorous tone, “You saw my paper, right?” Of those that did complete a second drawing, the quality of the drawing was much less than that of the first. For example, Tyler’s second drawing did not resemble anything he ended up designing. In fact, it seemed that he used his drawing time to make a humorous sketch. After drawing it, he held it up to his group and stated, “Check it out!” The group laughed and then quickly continued onto the computer to design.

To summarize, five participants expressed frustration with their ability to draw on paper, and all left out certain design aspects that may have been difficult to illustrate on paper (different perspectives of the fish). Many of the components absent on their paper drawing ended up in their CAD drawing. Instead of choosing to better their paper drawings, participants chose to express their conceptions through other forms of models.

Navigating CAD drawing spatial challenges. Results showed that participants navigated spatial challenges during the development of their CAD drawing in four ways: CAD drawing iterations, receiving assistance, verbal modeling, and gestural modeling. It must be stated that many of the spatial challenges were not overtly negotiated until the CAD drawing was printed. It is probable that the participants had negotiated many of the spatial challenges during the development of the CAD drawing, but some may have

occurred later. Thus, any discussion that happened during the structured discussion actually occurred with the 3D printed model. Below, each of these themes are explained.

CAD drawing iterations. The process of creating a CAD drawing was inherently iterative. In order to navigate spatial challenges each participant completed many quick iterations of each design component. Table 13 illustrates examples of iterative processes certain participants went through in order to add one component to their design. It should be mentioned that participants may have returned to the same component later to complete further iterations. In fact, students often returned to components they had previously placed on their designs to align and angle the feature. In the examples provided, I did not observe the alignment of the features.

Table 13.

Iterations of CAD drawing design components

Participant / design component	Shape / extrusion	size	translation	rotation	perspective	Total	Total min.sec
Greyson / fin	4	3	5	4	8	24	3.23
Preston / horn	0	11	8	0	12	31	1.45
Billy / caudal fin	18	4	5	8	17	52	4.34

Shaping the object dealt with the spatial transformation of a 2D circle that would simultaneously transform a 3D cylinder into a customized shape. Billy used this design tool quite a bit when designing his caudal fin. The sizing tool helped all participants deal with proportion in their design and the translation and rotation tools allowed for the placement of the design features on the fish. The visualization tools allowed participants to see their design from a more advantageous angle so that design would be easier. All of these tools also assisted in establishing symmetry, balance, and sometimes even implied movement in the participants' design. Table 13 is not meant to draw patterns from the types of iterations students used, rather it is meant to reveal the quantity and relative quickness of iterations completed by participants during the development of their CAD drawing. These iterations were a main way that students navigated spatial challenges involving the CAD drawings.

Receiving assistance. Participants sometimes asked for assistance in order to complete spatial challenges. For example, when Chase was trying to align his pelvic fins he decided to ask his partner for assistance. When that didn't work, he asked the researcher.

Chase: (Talking to Tyler and pointing to his computer screen) What just happened here?

Tyler: It just won't have fins—just be flopping around in the water.

Chase: Yeah, I'm having trouble aligning the fins.

Tyler: Yeah, I think you just have to keep doing it like that.

Chase: Really? (Raises his hand and researcher comes to assist)

Researcher: What's up, Chase?

Chase: I'm having trouble aligning the fins.

Researcher: Okay, click on alignment. It's up here (pointing). Now get to a top view.

Chase: Oh! Okay.

Sometimes participants received spatial assistance without asking. For example, when watching Chase place a horn on his fish Tyler stated, "What just happened? Undo. Undo. That is the wrong direction. It should be the other way to fend off predators." In this example, Tyler's verbal directions assisted Chase in the placement of a design feature.

Verbal modeling. Similar to paper drawings, participants used verbal modeling in order to assist in expressing ideas that were difficult to represent using CAD. It seemed that in recorded cases of verbal modeling, the modeling helped to explain movement, technical difficulties with the final CAD drawing, or internal linkages not presented on the CAD drawing.

When describing his fish's pelvic fins Bradley stated, "The fins aren't glued in place-- they can move around." He also stated, "The tail is larger so it can help it angle downward to suck up prey." Another reason for verbal modeling was to help correct flaws in their completed design. For example, Preston stated in the first structured argument, "Yeah, my eyes are lopsided. They are supposed to be symmetrical. I can fix that next time."

The groups also had a chance to write explanations for their changes to their fish. Some of the explanations involved verbal modeling that assisted in the description of their ideas. For example, Preston wrote that the spikes on the back of his fish "came from the backbone." Preston's explanation illustrated an internal linkage to design that was not evident in his CAD drawing. Tyler explained in his writing that the holes near the mouth

of his fish were, “filters [that] let the sand come out,” again implying movement not overtly noticeable on his CAD drawing.

Gestural modeling. Again, gestural modeling occurred simultaneously or along with verbal modeling. In regards to the CAD drawing, it was used to assist others in its spatial placement of particular features of the CAD drawing or to better explain movement not presented in the CAD drawing.

During the development of the spikes of his fish, Preston pointed to the top of his fish “They go up there. The spikes are part of the backbone.” Pointing to the computer screen was commonplace and often involved spatial assistance. Gestural modeling also occurred when participants discussed movement or functions of their design features. For example, Chase was trying to persuade his small group to use his design idea for the fish’s mouth. He then chose to explain how the mouth would work. Chase said, “This is how the mouth should work,” while he put his hands up to his face, closed them from the side, and also closed his mouth at the same time. This movement was not overtly illustrated on the CAD drawing, but the angles of the mouth made it possible for one to imagine such movements.

Summary of spatial challenges. In this subsection I presented the spatial challenges involved in creating a paper drawing and a CAD drawing and participants’ methods to navigate said challenges. Although the challenges were similar in nature between both methods of design-based modeling, participants seemed to engage more often in spatial challenges when developing the CAD drawing. This is evidenced by the lack of erasures during the paper drawing and the multitude of iterations with each design feature during the CAD drawing. It was also interesting that students only thought to

represent one side of their fish, and very little effort was put toward representing depth or symmetry on their fish in their paper drawing. In contrast, depth and symmetry were a major concern of participants during the development of the CAD drawing. Placement, proportion and manipulating perspectives challenges were also very different for the CAD drawing. Placement and proportion involved several manipulations of the 3D design feature in 3D space, while they involved merely connecting a 2D design component to the fish with one stroke of a pencil. Participants were not observed manipulating their perspective except for once on the paper drawings, yet this happened multiple times for each design component using CAD software.

Although participants relied on verbal and gestural modeling to navigate spatial challenges present in both methods of design, more of the spatial challenges that participants encountered while trying to represent their ideas in the paper drawing were represented through other modalities of models. In contrast, though it required many iterations, the CAD drawing seemed to allow students to attempt to represent symmetry, proportionality, depth in ways that paper drawings did not. Also, CAD seemed to provide a more intense spatial experience than did the paper drawings. Movement seemed to be a spatial challenge that neither paper or CAD drawings represented well and balance was one that both represented similarly.

It was interesting that all students said that they would rather use Tinkercad to design than using paper. It was also unexpected that Billy, Greyson, Chase, and Logan all stated that using Tinkercad was somehow easier to represent their ideas especially understanding that the process of design on Tinkercad involved so many spatial

challenges. Perhaps the 3D space and the tools provided in the program allow participants to engage in spatial challenges that they often ignore when drawing on paper.

Impact on Spatial Abilities Summary

The participants in this study entered the study already having considerable spatial experience, high science grades and confidence in their spatial task performance. The fact that participants scored highly on their spatial abilities pretests is in concordance with current theory that positively correlates high scores on spatial tests and high levels of spatial experience and high science scores (Doyle, Verner, and Cherney, 2012; Bodner & McMillan, 1998).

Current theory in spatial research contends that spatial abilities can be taught and that paper folding, paper drawings, constructing physical or virtual models, and the use of 3D models are some of the strategies a teacher may use to build spatial thinking skills (Baker & Pibern, 1997). In the context of this study participants were involved in most of the aforementioned spatial building tasks and were required to engage in intense spatial tasks through the CAD software they used. In fact the findings reveal a hierarchy of these spatial learning tools that adds to Pavlou's (2009) findings involving the differences in the thinking of children when building a 3D model as opposed to a 2D drawing. In their study, students often omitted or ignored certain features when developing a 2D model, but had to deal with symmetry and balance when creating a 3D structure with their hands. This is similar to our findings with CAD software, but we add that manipulating perspectives, proportion and placement are also spatial challenges relatively absent or less challenging in 2D paper drawings. Another important finding that seems to paint CAD as a superior spatial learning tool is the amount of iterations students completed as

compared to drawings. Though I do not contend that the intervention is responsible for the increased scores of participants spatial task performance on spatial abilities tests, the intense spatial challenges they endured are experiences known to build spatial abilities, and their confidence to perform spatial tasks on CAD software increased.

Model-based transformational reasoning is a negotiation among visual-spatial thinking and other types of reasoning among one or more models (Ramadas, 2009). In order to navigate spatial challenges in this intervention, participants engaged in model-based transformational reasoning in several ways. The findings support Subramanian and Padalker's (2009) assertion that students needed a combination of visual and gestural assistance for verbal explanation of models. We add to this theory that students also use gestures and they use them during the building of models. Yet we add that students also benefit from gestural and verbal modeling to assist in CAD drawing development when working in teams.

RQ 2: Impact on Argumentation

In this section, I present findings related to how design-based modeling implementation impacted participants' argumentation. First, I present findings involving when argument occurred during the intervention. Discussion then moves to the evaluation of participants' arguments using the IASCA (Mendonca & Justi, 2014) as well as how well the IASCA functions when faced with evaluating argumentation in a design-based modeling context. I then relate these findings to the process of modeling described by the MMD (Justi & Gilbert, 2002). After describing these relationships, discussion will begin involving how and when participants used different modalities of models for discussion or argumentation, and then I will present participants' ideas of how different modalities

of models assisted them in argumentation. This moves discussion onto how a sense of ownership of the models and their ideas impacted participants' argument. This section will end with a summary.

When Argument Occurred

In this study there were several scheduled opportunities for participants to argue scientifically using models. All groups used all scheduled time to argue that their particular design features represented structures that would function well in the new environment. A surprising finding was that unscheduled argument occurred at several points during the intervention.

Unscheduled argument occurred during time when students were developing their paper and pencil drawings and their CAD drawings. For example, while Greyson developed the mouth on his model, Tyler began to inquire about his design and ultimately they engaged in argument.

Tyler: Is that a duck?

Greyson: No it is not a duck. The mouth is like the tongs we used remember?

Tyler: That is a beak!

Greyson: No, it is a mouth. (Laughing)

Tyler: Well that looks awfully flat and the tongs were curved and had filters. Yours doesn't have filters. (Tyler then looks back at Chase's CAD drawing)

In the example above, Greyson did not make any noticeable changes to his mouth design after Tyler's comments. Also, Greyson did not open the same dialogue with Tyler again. For the most part, the scientific arguments that occurred during CAD drawing development were choppy and short in duration. Also, these discussions would often

happen when a participant asked for someone to look at their design. Billy was one that often asked others to look at his design. “Chase, look at this!” he said as he turned around his computer to show his CAD design. Chase asked, “What? There is some big stuff on the top, that is for sure. What is it?” Billy answered with a justification about a retractable fin and then discussion quickly ended as Chase began to design his fish again.

There were two distinct times when all students seemed naturally drawn to argument without prompting. In fact, it was difficult to stop them from scientific discussion. Both day two and day four of the intervention began with students entering to find their 3D prints presented on a table in the front of the class. Upon entering the classroom students quickly went to view, handle and discuss the models. The talk began with comments like “Cool!” and “Oh, this turned out awesome!” Then the comments quickly turned to questions, and then to scientific argument. Logan picked up Greyson’s model and asked Chase, “How would this mouth work? That is impossible!” To that, Greyson responded, “It can find the prey underneath the sand, like this (Pointing to the tongs used the day before).” This began an in-depth, yet informal scientific argument that lasted until the bell rang. In isolated cases, many participants focused on one aspect of a certain model. For example, after several participants spoke about how the pelvic fins’ angle of Billy’s design would make the fish immobile, holding his 3D printed fish model close to his chest while walking away from the group Billy stated, “Hey, it has feelings you know. It is molded plastic, but it has feelings.” Although this could be seen as light-hearted candor, in the end Billy expressed that he felt his design was too harshly judged, and blamed the one student who began this criticism of the pelvic fins. It was evident that Billy began to take the arguments against his design component personally during this

session and in this informal environment several people talking at one time was overwhelming for him. In both day two and day four, informal scientific argument started as soon as participants viewed models and continued until the bell rang. I actually had to ask students to please stop scientific argument so they could get the directions for the day's activities.

In summary, participants became involved in scientific argument during several points in the lesson that were somewhat unexpected to the researcher. These points were when students were scheduled to design their models and when they entered the class to view printed 3D models. One aspect that all of these time periods had in common was the participants' viewing and/or handling of models. Whether the presentation was by the one who modeled or whether the model was just out to see and/or hold did not matter: aspects of the model were questioned and argued. These informal argument sessions allowed participants a preliminary look into how others felt models fared and how their arguments would be accepted among certain members of the group. Yet, due to the informal nature of the context, participants' arguments were raw and at times seemed to upset certain participants.

Argument and the IASCA

In this study, students are simultaneously involved in design processes and modeling processes. The IASCA is an instrument developed specifically for the analysis of arguments "produced in modeling-based science teaching contexts (Mendonca & Justi, 2014, p. 215)." For this reason, I chose this instrument to investigate how it might fit in the context of this intervention. The data revealed several patterns of how argument in this study fit into the IASCA or where the IASCA fell short as an evaluative instrument

for design-based modeling. The subcodes related to this central code are design in argument and Levels of argument. Several categories exist under the subcodes as well. This section presents findings related to Argument and the IASCA.

Design in argument. Data revealed that part of the design process became a part of scientific argument. One portion of the design process (design challenge constraints) not included in the IASCA are involved in and essential for scientific argument in this context. This subcode was categorized into two sections: design challenge criteria and explicit vs. implicit. Below, I present these findings.

Design challenge criteria. The following excerpt of scientific argument during the development of participants' second CAD drawing provides an example of the importance of design process in this context. The bolded sections of the example are directly related to the design challenge criteria: the fish's new environment involves prey that live just beneath the sand.

Billy: What about fins that can dig? (Digging motions with his arms) That would work.

Logan: I don't know about that. How do the fins will do that?

Billy: They should be more paddle-like, so they can dig into the **sand to uncover the prey**.

Logan: I think they should just be flat—no angle like we had. That way it can glide **across the bottom** without dragging its fins. It can move smoothly **across the bottom**.

Like the carp, catfish and what's that thing—the st... they don't use their fins to dig, but they are **bottom feeders**. {Refutation; Theoretical justification; Empirical justification}

Billy: Yeah, but skates use their fins or whatever to dig in the sand and they [i.e. carp, catfish] **might not have to get under the sand**.

Logan: I would rather have a flat bottom fish. That is something that is common in nature—skates, stingrays, catfish and stuff like that are all kinda flat. Fins like this (Puts arms out flat-like) instead of like this (Points to first 3D print pelvic fin).

In the excerpt above, the bolded words are directly related to the environment for the new fish as demarcated in the design challenge. Thus, Billy and Logan are making justifications based on the criteria of the design challenge. Although they are using theoretical justifications (eg. pelvic fins can be used to dig in sand) and empirical justifications (eg. making reference to observational data like the form of stingrays and catfish), the justifications based on design criteria are equally as valid. In this context, the theoretical and empirical justifications would be of no use without first taking into account the design criteria justification. These are not theoretical or empirical justifications, but they are a basis for their decisions. Much like an engineer that dismisses the constraints involved in their designs, Billy and Logan's arguments would be less valid without these criteria as a part of their argument.

These criteria for the design challenge were not only used to support claims. In some cases the criteria were used to refute claims that were justified by similar design challenge criteria. For example, the following excerpt presents participants' use of several separate design challenge criteria: murky water, shallow water, prey located under the sand and predators that attack from above. Again, the design criteria justifications are bolded.

Greyson: I said it needed this light thing **because the water is murky**.

Chase: I don't think so cause that will just alert it to **predators**.

Tyler: Yeah, but anglerfish use it as a lure.

Chase: But the **water is shallow**.

Tyler: But it is also **murky and no light gets through**.

Greyson: Yeah, true, true. (Erases bioluminescent design feature)

Chase: Just think with the light: I'm a **predator** (Opens mouth) **They attack from above**. Why is the sun at the bottom?

In this argument the three participants are having to reason through several different constraints for their design in order to justify their design decision. In this particular example, participants use design challenge constraints as both a support for the claim that bioluminescence is needed in the model and also as a refutation for that claim. It is evident that Greyson, who had developed this idea in the first place, had not thought of the predator being attracted to the light of his bioluminescent design feature. What is interesting is that participants are scrutinizing these conceptions of form and function and their connection to the environment through thought experiments and reasoning in the face of design challenge constraints.

Explicit vs. implicit. Another interesting pattern revealed in the data was the explicit mention of this design criteria tended to wane as the modeling process matured as compared to the MMD. As the last example revealed, participants explicitly mentioned the design constraints and used them as justifications and refutations. Theoretical justifications and empirical justifications seemed to take a backseat to design challenge constraint justifications. Later in the modeling process though, the mention of design criteria became more implicit. Below is an example of a typical argument after empirical testing and after the printing of the second 3D printed model. This occurred on the last day of the intervention. Again, the design challenge criteria are in bold.

Chase: So with my fish I started by changing mouth so it is more like a stingray and it also has inward facing teeth so that it can trap its **prey** on the inside while destroying them.

Greyson: Where are the teeth?

Chase: They were too little to put in, but I intended to put them in. If we had more time I think I could have done it.

Preston: I see that it looks like it could scoop up the **prey**, but it looks like it would scoop up **sand** too.

Chase: Well, it has these filters too. They allow the **sand** to filter out while eating.

That is what these holes are for—like a stingray and the tongs that had the holes in it to filter the rice out.

This example reveals the implicit nature of the design constraints further along in the modeling process. At this point all participants are very familiar with the design challenge criteria, so it is mentioned less. Although it is implicit, it still plays an important role in the argument. Preston provides a refutation of Chase's model when he mentions that it may scoop up sand. This implies that the prey is under the sand, which is the design challenge constraint. At this point though, like Chase, most participants had thought through the design challenge constraints. As this example reveals, theoretical justifications (eg. inward facing teeth trap prey) and empirical justifications (eg. mentioning the simulation involving tongs with holes) play more of a central role than they did earlier in the design-based modeling process. Thus, Level 3 arguments involve a more implicit involvement of design challenge constraints. Compared to the MMD, more

explicit mention of design challenge constraints are mentioned in stages one and two of the MMD, while in staged three and four their mention is more implicit.

Levels of Argument

The aforementioned IASCA categorizes arguments into three levels. In level one a claim is justified in one of three ways: theoretically, empirically, or representationally. Level two is characterized by a claim justified both theoretically and empirically while in the process of making sense of a phenomenon. In fact, both level one and level two arguments are characterized as having sense-making purposes. A level three argument also is characterized as a claim justified both theoretically and empirically, but the argument's purpose is to persuade instead of make sense of the phenomenon. In the design based modeling context of this study, participants are constantly comparing models. The data revealed patterns within this subcode: Dual purposes of argument, Absence of Level 2 arguments and MMD and SCA comparisons.

Dual purposes of argument. While students seemed to be making level one arguments, sense making and persuasion were an equally important purpose of the argument. The following excerpt provides an example of this intertwining of purpose in argument.

Billy: We also made the tail larger so that allows it to be or to have more agility.

Tyler: Wouldn't a bigger fin make it weigh more and slow it down instead of speed it up?

Billy: Well, it would... it would make a current to help it move forward at a quicker speed.

Logan: Because it is bigger it displaces more water so it would be able to move quicker.

Chase: But wouldn't moving more water use more muscles and tire out the fish more than before?

Using the IASCA, I now present the argument coded for claim and justifications. The claim is represented as bold lettering while the theoretical justification is represented as a single underline. The above data are summarized as follows:

The model should have a larger tail because a bigger fin displaces more water to help it move forward at a quicker pace. {Level 1.T}

The model should not have a bigger caudal fin because its weight will slow it down and using more muscles will exhaust the fish. {Level 1.T}

The context of this argument is important. At this point in the lesson participants are only using prior experiences and knowledge to justify their claims. During this first structured discussion, I made sure to reiterate that in order to appropriately back up claims, theoretical justifications should be cited correctly and empirical justifications would also be needed. This would lead us into the second day of intervention where all participants were involved in an investigation. Still, the context of this design challenge was one in which persuasion was commonplace during scientific argumentation with the whole group. Logan and Billy are presenting their model as a plausible solution to the design-based modeling challenge: develop a plausible modification of a fish model that could survive in a specific environment. Thus, based on their prior knowledge, all participants are arguing for their own model. In this excerpt sense-making is also taking place. The theoretical justifications and refutations are not sound and are somewhat

indecisive, as they are posed as questions. Therefore, there is a negotiation of scientific knowledge between participants that are sharing prior knowledge.

During the last day of the intervention, again a whole group structured discussion occurred. At this point participants had engaged in an investigation involving the form and function of certain mouth designs. At this time participants were armed with empirical justifications in order to justify their claims. Below is a summarization using the IASCA of an excerpt during this whole group structured discussion.

Chase: So with my fish I started by changing mouth so it is more like a stingray and it also has inward facing teeth so that it can trap its prey on the inside while destroying them.

Greyson: Where are the teeth?

Chase: They were too little to put in, but I intended to put them in. If we had more time I think I could have done it.

Preston: I see that it looks like it could scoop up the prey, but it looks like it would scoop up sand too.

Chase: Well, it has these filters too. They allow the sand to filter out while eating.

That is what these holes are for—like a stingray and the tongs that had the holes in it to filter the rice out.

Chase: **The model needs a mouth with inward facing teeth** so it can trap prey inside while destroying them. This is like a stingray.

Chase: **The model needs a mouth with filters** that allow sand to filter out while eating this is much like a stingrays mouth and like the tongs that filtered rice out.

This excerpt reveals that there is a mix of sense making and persuasion during the argument. The context is again important to understand. All participants are putting forth a model that they deem as plausible. Therefore the main purpose of the model is to persuade. The sense making in this argument is different than the first. The refutations that Preston and Greyson propose are not refuting the science behind Chase's claims. Instead, they seem to be trying to make sense of the model design. For example, Greyson asks where the teeth are and Preston asks about a certain shape of the mouth. In both of these instances the participants are trying to make sense of Chase's model. As opposed to the first example, all participants have gone through an investigation in which they have observed the stingray's mouth and how it feeds, and also recorded and analyzed data through simulation using tongs, spoons and other similar devices to investigate how certain structures gathered food from underneath a thin layer of sand. Therefore, in this case there is little sense making involving science knowledge. This relates to Mendonca and Justi's (2014) classification of a Level 3 argument: that persuasion is the main purpose.

The absence of Level 2 arguments. What did not show up in this study were Level 2 arguments. The structure of the design-based modeling lesson was one that constantly encouraged argument for or against a model. This means that persuasion was usually a major part of the argument even when in small groups. On the day that participants completed an empirical investigation participants had no time for the open argument of their models. Perhaps if they did, more sense-making would have taken place. Findings revealed that students went from a Level 1 argument where they based a

claim on a theoretical and/or a design challenge constraint, to one in which they combined theoretical, empirical and design challenge constraints to justify their claims.

MMD and SCA comparisons. Data in this study revealed that all Level 1 arguments occurred during stage one or stage two of the MMD. All Level 3 arguments occurred after empirical testing. Participants in the study had no experience or prior knowledge of empirical testing that dealt with this concept; therefore, the empirical justifications needed in a level 3 argument were not available to participants until after they were able to be involved in an empirical investigation.

In summary, design challenge constraints played a major role in scientific argumentation in this particular context. Participants use them as justifications and refutations and at some points modified or rejected a previous model due to these design challenge constraints. This finding adds a certain depth to Azevedo, Martalock and Keser's (2015) findings on discourse in design-based classrooms. In this study, we explicated what argument might look like compared to model-based lessons that have less of a focus on design challenges. In Mendonca and Justi's (2013) previous study in which they used IASCA to analyze scientific argument, the process of designing the model was not a focus. In order to analyze or evaluate scientific argumentation in a context similar to the one in this study, making reference to design constraints is must. This is an important clarification for argument in a design-based modeling context. This finding directly relates to Mendonca and Justi's (2014) call for research to establish the IASCA's generalizability to other modeling contexts. Also, a pattern in the way design challenge constraints were mentioned was related to the MMD stages and the IASCA Levels. Table 14 presents these patterns. Possibly due to the short duration of this study,

its design-based modeling structure, and the prevalence of persuasion during arguments we found no Level 2 arguments. Also, Table 14 explicates the relationship of when design challenge criteria was more explicit during this study.

Table 14.

MMD and SCA relationship to design-based modeling

MMD Stages of Development	SCA Levels Present	Design Challenge Criteria
Stage 1 and Stage 2	Level 1	Explicit
Stage 3 and Stage 4	Level 1 and Level 3	Implicit

Model Utility During Argument

During the course of the modeling process, participants used and viewed models' utility in different ways. Interviews were the main data source that provided the participants' views while observations were the main data source that provided participants' behaviors with the three models they constructed: paper drawing, CAD drawing, and the 3D printed model. This section will first present findings related to participants' thoughts about the utility of different modes of models. Then I present findings that dealt with participants' uses of models through observational data.

Participants' views of model utility during argument. I asked questions during both the preinterview and the post interview that dealt with this topic. The subcodes that emerged from the data related to participants' thoughts about the utility of models were: accuracy, perspective, material, generative and explanatory.

Accuracy. In general participants felt that accuracy was an important aspect of a model when it came to argumentation. Five out of seven students mentioned the benefit of 3D printed models for being able to make a model that would have sharper accuracy

than other physical models. In his first interview, Tyler stated, “I feel like with my own hands I could probably put it together closer to what my idea in my head would be (than a drawing), but with a 3D printer I would be like have a better way of getting those exact angles than I would with my own hands.” In his second interview he expanded on this idea and stated, “I felt like our 3D print was a physical manifestation of the ideas we had.” Billy stated, “I don’t think you could get those teeth right with Playdoh. (Second interview)” When speaking about using the CAD program he stated, “It allowed me to make things how I actually want them to be.” Only Greyson stated that hand-made models would make a more accurate model than a 3D printed model.

It should be noted that throughout the intervention I reiterated that models are not physical manifestations of nature: they have a particular purpose. Still, as the excerpts reveal, most participants thought that the 3D printed model was something that more closely resembled what they wanted to portray in order to assist them in argument.

Perspective. Three participants (i.e. Garrett, Logan and Greyson) spoke about the added benefit of viewing 3D models from several different perspectives. Garrett stated, “3D is better because you can see stuff better because it shows you every single angle. (First interview)” Another example was during Logan’s second interview. “With 3d you get to see so many different perspectives it was better for me to understand. It is more useful than a drawing for arguing.” Greyson spoke specifically about the 3D printed model that he used during argumentation. “Well you could use different perspectives to show all sides of the fish. Things were on all sides of the fish, like the fins and the spikes are on the bottom. It helped me more than the drawing.” Being able to view a model from several perspectives seemed to assist in argument for these participants.

Material. Several participants commented on durability of the material used in the 3-D printed models. Most viewed this as a positive for argument. Billy stated, “Well, making it out such material that it doesn’t come in a ready-made hardened form. For example, play doh it could bend or something. I don’t think it’s [3D printed model] bendable.” Billy went on to comment about his worry about passing it around during argument if were to bend. Chase also commented about the 3D printed model in the second interview. “I think that Playdoh wouldn’t have the structural integrity to have fins and have the whole thing remain upright without just collapsing into a mound.” Though Chase also highlighted the positives of constructing something by hand. “Some things a handmade model can do that a 3D [printed] model can’t is different textures and colors. And if you were to make it by hand, you have a better grasp of what the materials that make it.” So overall, most participants thought the durability of the model was a positive aspect of the 3D printed model for argumentation, while the use of varied materials for a hand made 3D model would provide a benefit as well.

Depth. Overall, participants viewed depth as a benefit for argument. Preston gave an example of how a 3D topological map could help you better understand intricacies of the surface than a 2D topographical map. “Models help us to understand the depth. Like on a topographical map in a drawing you don’t know where the bumps might be between the lines (Preston, First interview). Chase provided an example from the intervention in his second interview, “With a three dimensional one you could tell that the eyes bulged out of the head to give it 360 degree vision and that the horn was rounded to penetrate better. But with a 2-D model you can’t really tell that. And, yeah, it is easier to support your arguments when you have depth to them.” Chase’s comment illustrated the visual

dominance that he perceived that the 3D printed model had over the 2D paper drawing. It also assists in revealing the detailed thought that went into creating his model and his arguments.

Generative vs. Explanatory. If a model is generative, it can still assist in argument because it will assist the modeler in coming up with their ideas for the argument. An explanatory use of a model would also assist in argument, but its use would be more important later in the process of argument. Billy and Logan were the only two participants that explicitly used a paper drawing during the whole group structured discussion. They picked it up to show and use as a reference while they argued. Billy stated in his second interview, “I used it because I didn’t get to finish some parts on the [3D printed] model.” All other participants spoke about their paper drawing as a generative tool. Greyson stated, “I used the drawing to help me remember what I wanted to make.” Preston spoke about the paper drawing in second interview as a generative tool, “I used it the first time to put down my ideas, but the second time I just did Tinkercad.” All participants spoke of the 3D printed model as something that helped them explain or support their arguments.

“I think that again the [3D printed] model it’s a lot better than a paper-pencil drawing. And especially in this project. I feel like you needed to show a little more [than a paper drawing] to actually support your arguments (Logan, Second interview).”

During his second interview, Chase mentioned a specific part of his 3D printed model that helped him to explain. “The jaw it helped me explain that it was larger than a normal jaw and how it had backward facing teeth in the general idea of it.” The fact that

paper drawings were seldom used during the actual argument may mean that they served more in a generative role. All 3D printed models were used during the whole group structured discussion.

Participants' uses of models during argument. Argument with models involves the combination of different types of modeling, so participants are involved in model-based transformational reasoning as described by Ramadas (2009). In order to analyze participants' behaviors during argument, I used a behavior protocol to analyze how students used different modalities of models. The findings revealed that participants used models to support argument in three ways: for reference, rotation, and gestural movement. Table 15 presents frequency counts for these three behaviors in three different contexts. The three contexts were selected because they presented the most activity for behaviors in each of these contexts and in order to compare findings across contexts. The second structured discussion presents a formal stage for argument with both the paper model and the 3D printed model accessible for participants. The second gallery walk was a more informal context where participants were able to speak to each other and their small groups about other groups' models. The paper drawing discussion presents a context where participants were arguing for each other's paper models without the use of a CAD drawing or a 3D printed model.

Table 15.

Frequency counts of behavior during argument.

Participants	Second Structured Discussion				Second Gallery Walk				First Paper Drawing Discussion			
	reference	rotate	gestural		reference	rotate	gestural		reference	rotate	gestural	
Billy	12	7	3		5	1	3		2	0	3	
Greyson	6	1	2		3	1	0		0	0	0	
Chase	7	3	3		5	1	1		2	0	3	
Preston	10	4	4		4	2	2		3	0	1	
Logan	7	1	3		6	0	1		0	0	2	
Garrett	4	2	4		5	3	2		1	0	1	
Tyler	absent	absent	absent		5	2	2		1	0	3	
Total	46	18	19		33	10	11		9	0	13	

Reference. The sub code reference could also be construed as gestural modeling because students are actually gesturing to refer to specific parts of the model in order to better explain something. Table 15 reveals the preponderance of reference behaviors during argument. In all contexts reference behaviors were more prevalent than either rotation or gestural movements.

Rotation. Table 15 reveals that rotation of the model during argument did not happen when only a paper drawing model was available for use. This is not surprising since the paper is two-dimensional, but several of the groups were sitting across from each other; thus, rotating the paper drawing model may have been appropriate in some circumstances.

Gestural movements. I define gestural movements as when participants re-create lifelike movements using a model to better explain some aspect of mechanical movement of their fish model. Participants used other gestures during argument that may be construed as dialogic gestures. For example, Chase shrugged his shoulders and nodded his head when he did not agree with Grayson's justification for his model. This gesture did benefit argumentation because Chase was able to show his disagreement, but this gesture did not have to do with model utility. With this reasoning the gestures coded in some way had to deal with either the paper drawing model or the 3D printer model. Table 10 reveals that gestural movements are somewhat common with the paper drawing model, but observation data revealed a difference in the way students gesture using the paper drawing model compared to the 3D printed model. When participants used gestural movement with 3D printed models they most often made the 3D printed model move in some way. When participants used gestural movement with paper drawing

models the movement typically involved the modeler gesturing as the model while only referencing the paper drawing sitting on the table. With both the paper drawing model and the 3D printed model, students typically used gestures to better explain some sort of movement.

During both the second structured discussion and the second gallery walk, participants had access to their paper drawings yet chose not to use them. During argument when only paper drawing models were available, students did not reference or rotate the model as much and any gestural movement was done apart from the paper drawing model. This finding is in concordance with participants' perceptions that 3D printed models assisted them in argument more than paper models. The findings on gestural movement support Subramanian and Padalkar's (2009) findings that gestures are often used to express a "dynamic situation" between the model and the phenomena. In this case, the dynamic situations were usually mechanical properties of the structures that were not able to be presented easily on the model. The findings also reveal that model-based transformational reasoning (Ramadas, 2009) is more prevalent with the use of 3D printed models in the context of argumentation. The detachment of gestural movement from the paper drawing model suggests that the transformational reasoning involved with the paper model is more of a verbal/gestural transformation instead of a verbal/visual/gestural transformation. In the case of the 3D printed model, the model was much more involved in the transformation, suggesting that a 3D printed model allowed for a more sophisticated level of transformational reasoning. Thus, a 3D printed model better assists participants in argumentation. In this study the data reveals that the 3D printed model better assisted participants in argumentation.

Sense of Ownership

Data analysis of observations and interviews revealed that all participants developed a sense of ownership in their model creations. The sense of ownership participants displayed assisted them in feeling proud of their accomplishments and impacted scientific argument.

Statements of Ownership. While involved in this intervention, participants developed a sense of ownership over the model and the ideas they formed for the argument. Near the end of the second day of design, Greyson and Preston engaged in dialogue that revealed a certain pride and a sense of ownership.

Preston: Ours is called the magical unicorn fish. Look at his horn. The predators will not have an easy time with him!

Greyson: Look at that thing, you can't say that mine is not going to be protected. Boom! How bout Carlos? Would you like to be called

Carlos? Yeah, I think he is a Carlos.

Although Chase was not the only one that contributed to the design of his 3D printed model, when speaking about it he spoke with pride. "I'm proud of the way I designed it." In this statement he even negated Tyler's contribution to the design. During design he also stated, "My fish just turned into a boss!"

Ownership behaviors. During the gallery walks, the behaviors of students revealed a high sense of ownership in their models. When Billy arrived in class he quickly went to go to view his 3D printed model. Soon afterwards, he began taking his model to each participant and telling them to look at his model. Grayson, Preston, and Chase also made sure to share their model with others. The way they shared their 3D printed models was different than the way they shared their 2D paper drawing models.

For example, when Grayson described his 3D printed model, he stated “I like my fish because it’s a super awesome fish.” When presenting his paper drawing model a fellow participant made a comment that his fish drawing looked more like a frog than a fish. He replied, “No, but I am not changing it. I am so bad at art.” While laughing, Tyler stated about his paper drawing model, “Mine looks like a whale.” When sharing their 3D printed models participants were prideful or mentioned positive aspects of their model, yet when sharing their 2D paper drawing models some participants used self-deprecating humor to dismiss inaccuracies of their model.

Model as an extension of self. In a few cases it became apparent that certain participants thought of the model as a manifestation of their intelligence in a way. This sense of ownership sometimes surfaced with a more negative bent. During the second gallery walk, many fellow participants criticized certain aspects of Billy’s model. When listening to their comments, he personified the model stating, “Hey it has feelings you know. It is molded plastic but it has feelings. It would work.” It was apparent that Billy felt the comments about his fish were a personal attack. Before the second design began, Billy and Logan could not compromise on certain aspects of their CAD drawing. For this reason they chose to work alone on their design while still being able to speak with one another as a small group. While they were designing they often talked about their ideas in a pleasant manner. After Billy’s model received harsh critique during the second structured discussion, he seemed to take it personally and blamed most of the critique on what he believed to be a conspiracy inspired by Logan.

“Yeah, I think one thing was just me being a human. I like when it’s my work. That it’s completely my work. But yeah, like I mentioned some of the ideas in my head kind of moved off and I did not agree with so I just felt like there really wasn’t much of an area for compromise in this case. Because as our fish turned out to be completely different (Logan, Second interview).”

Billy answered similarly when asked why he worked alone, yet while answering about how he felt when his work was criticized, he spoke about Logan.

“I felt that someone was really trying to convince other people that mine was truly not that good. And I believe in fact that it was my partner. I felt the my arguments were just as good and that my design was just as plausible as others.”

This dialogue illustrates the attachment that some participants felt to their model.

In summary, all participants developed a strong sense of ownership over the 3D printed model that was not apparent for the paper drawing that they created. The difference in the way participants spoke about different types of models was surprising. When looking at the data it seems that there was a fair amount of apathy when it came to constructing a paper drawing. In contrast, participants’ comments regarding their 3-D printed models and their CAD drawings were more prideful and serious. Although during model development, the sense of ownership participants tended to be very positive, this same sense of ownership made critique seem a personal attack and difficult to stomach for Billy.

Impact on Argumentation Summary

This study sought to understand if and how design-based modeling fostered participants' argumentation. The findings in this study presented several ways that design-based modeling fostered argumentation. Gilbert and Boulter (2000) suggest that modeling is a catalyst for scientific discussion. The findings in this study corroborate this suggestion. It was surprising for the researcher to see spontaneous and unscheduled scientific argument begin before class started on two out of the four days in which participants engaged in the study. There were several other instances of spontaneous scientific argumentation throughout the design-based modeling process, but in most instances, these occurred in conjunction with the public viewing of CAD drawings or 3D printed models.

Using the IASCA reveal other impacts that design based modeling had on argumentation of the participants. In this study we found that the design challenge criteria was a crucial part of scientific argument for participants. In fact, without reference to design challenge criteria, scientific arguments in this context would many times be considered faulty. Another finding related to design challenge criteria was that it often appeared explicitly early on in the modeling process as described by the MMD. In relation to the IASCA levels of argument, the explicit mention of design challenge criteria more often occurred during level one arguments in this study. The context of the study also seemed to encourage persuasion more than previous that used the IASCA to evaluate argument (Mendonca & Justi, 2014). In this study students were often negotiating between several different models while persuading each other that their idea would work

better than others; thus, the context of a design based challenge (one that poses a problem with many plausible solutions), is one in which pure sense-making takes a less vital role. Sense-making is intertwined with persuasion instead. For this reason, level II arguments are absent in this context. The IASCA levels are tied somewhat ambiguously to sense-making and persuasion purposes; stating that the *main* purpose of a level 2 argument was sense-making. With many arguments involving a dual purpose and because the IASCA did not provide evaluative components that included design challenge criteria, it is not a good fit for evaluating argument within the context of design-based modeling.

As referenced in the spatial abilities section of the study, model-based transformational reasoning is apparent during argumentation in the context of design-based modeling. As found in a pilot study, when faced with a choice between paper drawing and CAD drawing, students will quickly bypass paper drawing. We found that this was also apparent with the use of models during argument. Participants rarely addressed their paper drawings during argument. When observing the behaviors of students while they argued with paper models or 3D printed models there were differences also. Gestural modeling was more attached to the 3D printed model, while the 2D model was only sometimes referenced and never used to gesture with. Participants are overwhelmingly stated that 3D printing models assisted them with argumentation more than 2D paper drawings. Although paper drawing models tended to play a more generative role for students in this study, accuracy, perspective, depth, and material of material were all aspects that participants felt the 3D printed model better provided them with assistance during

argument. Participants' perceptions we're in concordance with their observed behaviors. Thus, I conclude that 3D printed models assisted students in developing and employing scientific argument while in this particular context.

This study supports Fortus et al. (2004) suggestion that design-based instruction and creating models creates a sense of ownership. Yet, it adds that this sense of ownership is different between modalities of models. Findings revealed that creating a 3D printed model resulted in a much stronger sense of ownership among participants than did a paper drawing. In fact, student often dismissed drawings altogether as a means to argue. During argument, this sense of ownership was shown to heighten certain students' sensitivity to criticism. This was evident when Billy felt that critique of his model was a personal attack. Thus, the pride and intellectual attachment that participants demonstrated through sense of ownership related to their 3D printed model enabled a more emotionally charged scientific argumentation.

Summary of Chapter

This study sought to investigate how design based modeling impacted the spatial abilities and argumentation of seventh grade participants. The findings revealed multiple impacts on both accounts. Participants entered the study with the high amount of spatial experience confidence and ability. In the particular context of the study, design based modeling provided multiple sustained opportunities for participants to engage in intense spatial challenges. In particular, the participants' development of CAD drawings and paper drawings revealed that spatial opportunities that were often ignored when developing paper drawings participants willingly navigated using visualization and

design tools within Tinkercad. Throughout the modeling process, model based transformational reasoning was one method that assisted participants in the development of their model. After intervention participants averaged a 10% increase on special performance tests, revealed increased confidence and profess their desire to continue this type of activity.

Findings also revealed several impacts on scientific argumentation. As evidenced by several unscheduled and spontaneous sessions of argumentation models developed during the intervention were a catalyst for scientific argumentation. Students perceived 3D printed models as providing more assistance for argumentation then their paper drawings and in some ways other physical models. Participants developed a strong sense of ownership for 3D printed models as opposed to their paper drawings. This sense of ownership engaged participants in a more emotionally charged form of scientific argument. Their behaviors during the intervention also revealed their preference for the use of 3D models to enhance their scientific argumentation. Model-based transformational reasoning also occurred during intervention. 3D printed models seems to facilitate a more sophisticated application of model-based transformational reasoning by students. Through the use of the IASCA to evaluate a scientific argument, it is apparent that the nature of argument involved in design-based modeling involves a more persuasive purpose and attention to design challenge criteria than the IASCA is equipped to measure.

Chapter 5: Implications

This multiple case study sought to investigate the impacts of design-based modeling on seven seventh grade participants' spatial abilities and argumentation. The study used previously developed theory in spatial abilities and argumentation to compare results (Yin, 2009). Using both quantitative and qualitative measures, this study investigated any gains in spatial abilities and the types of spatial challenges afforded by design-based modeling. Using the IASCA and other qualitative analysis, this study investigated impacts of design-based modeling on scientific argumentation. From the aforementioned findings this chapter presents theoretical implications, implications for technology in education, teacher education, practicing teachers and future research.

Theoretical Implications

Findings from Pavlou's (2009) study compared students thinking while creating two different types of models. It suggested that students are not challenged to think about aspects such as symmetry and balance when developing two-dimensional drawings. When developing a three-dimensional physical model, students were forced to think about those aspects (Pavlou, 2009). This study found that, though it was very brief and a minor challenge, participants did have to deal with balance in both paper drawings and CAD drawings. Symmetry, on the other hand, was another story. While developing their CAD drawings participants were engaged in a much more in-depth spatial challenge dealing with symmetry than they were when completing their paper drawing. Furthermore, depth and the manipulation of perspective were found to be more robust spatial challenges when students were involved in developing their CAD drawings as opposed to their paper drawings. These findings are important to build onto Pavlou's

findings, so that researchers may better understand the spatial intricacies of two methods known to build spatial abilities in school-aged children. This connects with current theory that purports a positive correlation between experience and spatial activities and performance on spatial tests (Toptas, Celik & Karaca, 2012). This also connects with current theory that purports that spatial abilities can be increased through training using CAD software (Martin-Dorta, Saorin, & Contero, 2008). Therefore, the Tinkercad software utilized in this study involves students in the viewing of objects in virtual 3-D space from several different perspectives as well as the transformation of 2-D figures into 3-D figures. These are spatial challenges not common in middle school science classes. Much like the words of Garrett in this study, “it gets easier when you use it more,” I suggest the vast amount and varied types of spatial experiences afforded by this CAD software makes it a superior spatial training method as compared to 2-D paper drawings. I suggest this with the caveat that in this case I referred to paper drawings without explicit teaching of technical drawing practices.

Ramadas (2009) calls for the investigation of how certain modalities of models are used in model based transformational reasoning. Findings in this study suggest that transformational reasoning does not only occur as students are explaining scientific ideas (Submaranian & Padalkar, 2009). Transformational reasoning also occurred while small groups were in the process of developing models. Their conversations did transform visual-spatial ideas into verbal and gestural models, yet they did so only to communicate to a partner how to build the structure they envisioned. This type of transformational reasoning usually occurred while students were expressing a mental model so that

someone could re-create it on CAD software. Thus, transformational reasoning happens during engineering design while working in collaborative groups.

Another finding dealing with model based transformational reasoning was that gestural movements using a paper drawing were disconnected from the actual visual model. In contrast, when participants used gestural modeling with a 3-D printed model, the model was a part of the gestural movement. In the case of the paper drawing model, there seems to be a transformation between only verbal and gestural modeling with the visual model being only an implicit component of model based transformational reasoning. Model based transformational reasoning with the 3-D printed model involved explicit incorporation of physical, verbal, and gestural modeling, allowing a more sophisticated and clear conveyance of ideas. This provides a more powerful argument for the use and development of 3-D models for the development of both spatial abilities and to assist in students' scientific argumentation.

Gilbert and Bolter (2000) suggest that models are a catalyst for scientific discussion. This study's findings support their suggestion and add that spontaneous and overt scientific argument can occur with the presentation of models. This may also be related to the sense of ownership that was evident in the development of the 3-D printed model. Fortus et al. (2004) suggests that students may gain a sense of ownership when engaging in design or the building of a physical artifact. This sense of ownership is often linked to engagement and further interest in the lesson and this study's findings support this notion (Fortus et al, 2004). Yet, this study also finds that in some cases a sense of ownership can invoke negative emotions among students during scientific argument.

More specifically, I contend that when one has built a sense of ownership regarding a self-constructed model, the critique of this model may be difficult on one's emotions.

Mendonca and Justi (2014) called for the investigation of the use of their IASCA within different model based contexts. The intervention I employed dealt with the construction of scientific models in the context of design challenge. As Mendonca and Justi (2014) suggest, the context of model-based instruction varies widely. In the context of design-based modeling, the IASCA does not seem to be an appropriate evaluation of argumentation. That being said, using the IASCA assisted in revealing an understanding of how design challenges change the structure of scientific argument. In order to evaluate scientific argument involving a model that students constructed in the context of the design challenge, the design challenge constraints should be seen as a crucial aspect of the argument. In all strong arguments, the constraints of the design challenge must be taken into account. Another aspect of the argument that differs from the context in Mendonca and Justi's study (2014) was the preponderance of persuasion within level one arguments. In their study, they provided many examples of Level 1 arguments and Level 2 arguments that were clearly for the purpose of sense-making. Most data in this study involving Level 1 arguments involved a dual purpose: sense-making and persuasive. The design based challenge context encourages the aspect of persuasion. This may be in part due to the availability of several correct models and/or the inherent competitiveness within a challenge. This also makes the IASCA a difficult instrument for argument evaluation in this context.

Technology in Education

Although technology has not been a primary focus of this study, I would be remiss not to mention the implications for technology in education that are inherent in the findings. More often than not the practice of modeling in science education is an exercise of developing representational paper drawings. Paper drawings are useful for this practice and much research has stated the benefit of it as a methodology (eg. Chang, 2012). Yet research has simultaneously heralded the development of 3D models (Pavlou, 2009). 3D models are categorized as superior to paper drawings because they allow students to dodge common misconceptions that are often communicated by premade physical models (Horowitz & Shultz, 2014) and students tend to develop a more in-depth conception of science knowledge (Loucha & Zacharia, 2012). When teachers do allow students to build models, it usually involves the collection of several different types of materials and the spending of personal money, a large cleanup after the lesson and an intense amount of prep work (Ratto & Ree, 2012). 3-D printing technology, as used in this study, could dismiss much of the headaches involved in developing a lesson involving the creation of physical models.

3D printers are slowly emerging in K-12 schools and at around the price of a promethium board, a school can purchase one to service an entire faculty. This study utilized a 3-D printer and free CAD software. Over the course of two days I printed out 12 3-D printed models, each taking about 25 minutes to print. The process involved transferring a file and then pushing the print button on the 3-D printer. An implication of this study is that using 3-D printing technologies to develop scientific models is a viable option for teachers at nearly any grade level. The students involved in this study were

able to create scientific models that were unique and could not be bought in stores because they represented the scientific conceptions of each specific small group. Students were able to use the CAD software without formal training and were able to develop a finished product in only 15 minutes. When given 35 minutes, students were able to make a complex and intricately designed finished product. The software program Tinkercad is filled with spatial opportunities, yet it is relatively easy to use. Although we were using it for seventh grade students, it could easily be used in upper elementary grades as long as proper scaffolding is in place.

The overarching reason to include technology in education in the implications section of this study was because many of the impactful findings in this study dealt with the use of 3-D printing technologies. The educative potential of these technologies are immense as evidenced by the spatial opportunities and their support of scientific argumentation found in the study. In summary, 3D printing technologies are a viable option to create physical models and science classes. Their low cost, ease-of-use, prep free hardware and easy cleanup should make 3-D printing technologies an easy choice for impactful science lessons.

Practical Implications

Contemporary science education reform calls for teachers to incorporate engineering practices within their science classrooms (NGSS Lead States, 2013). The context of this study provided an innovative and impactful way to do just that. That being said, the implications of this study for teachers in K-12 environments are many.

As described in this study, with the use of 3D printing technologies to design and create one-of-a-kind scientific models participants were involved in an incredibly

challenging spatial experience. Not only were participants involved in spatial challenges, but they also developed a sense of ownership over their model that kept them engaged and interested in the lesson at hand. In the meantime, the participants were engaged in authentic scientific and engineering practices. Furthermore, the 3-D printing technologies used in this intervention are relatively cheap, easy to use, and are becoming more prevalent in K 12 educational settings.

The context of the intervention was also unique to science education. Students employed models to test a solution to a given problem instead of simply trying to realistically represent something present in today's environment. This type of modeling in biology assists students in depth of thought about adaptations and form and function. It allows them to use their observations of real adaptations to create a solution to an evolutionary "problem". It is common knowledge that most science teachers do not facilitate the practice of modeling in their science classrooms. When they do it normally involves a paper and pencil representational drawing. These drawings take the form of a sketch a diagram or a colorful illustration. Having students develop three-dimensional drawings is difficult, especially when science teachers are not typically trained in technical drawing. Therefore, when teachers assign students the task of developing a paper drawing to represent a three dimensional object, students are put at a disadvantage from the start. In this particular study all students chose to draw a two-dimensional, cartoonlike version of a fish. Many were noticeably frustrated with their drawing and some chose not to draw a second time. Practicing teachers do not want to put their students at a disadvantage before the lesson that even really starts. Creating models of 3-D printing technology can allow teachers to put their students on a more

level ground. Several participants from the study claim today were bad at drawing or weren't good with making things with their hands, yet all participants were highly confident they can make a relatively complex figure using 3-D printing technologies. This finding has immeasurable implications. It is highly probable that there will be disparities in students' abilities when using CAD software, but what is different about this cad software is that it better allows students to deal with things like symmetry and depth through the use of its intuitive design and visualization tools. With this reasoning it seems nearly unfair for teachers to ask students to draw three dimensional figures on a two-dimensional sheet of paper and expect them to feel confident in their abilities. It seems the only way to do that is to either teach them technical drawing or to provide them a tool that will allow them to represent the three-dimensional figure. Of course drawing on two-dimensional paper has its uses in science education, but when the goal is to represent the three-dimensional figure, teacher should try to do their best in order to provide students the best tools for the job.

But why might teachers decide not to engage their students and modeling practices when research claims it to be highly effective for science teaching? One such reason is the cost of materials and the immense preparation involved in readying a class for an impactful modeling experience. Here I will reiterate what was said in a previous section. 3-D printing technologies can reduce preparation to a minimum and in most cases, reduce the cost of developing and executing key modeling experience for students. I'm not suggesting that every modeling lesson should utilize 3-D printing technologies, but I do suggest that 3-D printing technologies should be an option that teachers begin to think about when they're developing investigative science lessons.

Another reason to use 3-D printing technologies within science classrooms is to provide spatial experiences for students. It is imperative that teachers provide impactful spatial experiences and challenges to their students in STEM classrooms. Allowing students to talk about three-dimensional models allows them to practice model based transformational reasoning. Teacher should also encourage the use of multiple models. For example, when students begin to explain their 3-D models, teachers should encourage them to use gestures, sketches and writing to assist them and explaining their ideas. This will also encourage model based transformational reasoning to allow students to engage in this meaningful scientific practice.

This study's finding stresses the importance of allowing students to construct physical models in science classrooms. All students expressed that they felt that the 3D printed models assisted them in scientific argument more than the paper drawing. Also, they chose their 3D printed model in all but one case during formal scientific modeling. The one case that did not use the 3D printed model felt that they did not get to finish it. These models also allow teachers an intimate look into the students ideas; more information than a two dimensional model. In fact, this study revealed the different types of argument involved in paper drawing models and 3D printed models. Participants spoke about more sophisticated design issues when using 3D printed models. For example, instead of merely talking about the size of a pelvic fin as they did during the paper drawing, participants spoke about the perceived movement of the fish due to the angle and disproportionate sizes of the fins. This provides a much more in depth look at form and function: one that did not occur with paper drawing models.

Practicing teachers are often looking for ways to encourage their students to participate in authentic scientific argumentation. The study found that student created models were catalysts for scientific argumentation. Teachers should understand that students that create their own models want to view others' models and have the chance to discuss them. The viewing of these models will inspire questioning, explanations and argumentation. The study also found that providing an empirical investigation enhanced students' argumentation. Although the building of physical models as a catalyst for scientific argumentation, and also creates a sense of ownership that brings a certain emotion to the discussion. Teachers need to be wary of this, and make sure that students understand that the end goal of science is to understand the natural world and the best way possible. Students should understand that nearly all scientific models improve upon revision in order to better serve their purpose, and in science several different models can be used to describe one phenomenon.

In summary, this study provides many implications for practicing teachers. The use of 3D printing technologies provides a promising avenue for teachers to have their students take part in scientific modeling and argumentation. It also provides teachers a viable opportunity to integrate engineering and science practices in a meaningful way.

Future Research

As most research does, this research inspired many questions during the analysis of the data and the dissemination of its findings. This subsection will describe many areas in need for further research.

During the first and second interviews participants viewed 3-D printed models as being more helpful during scientific argumentation than other types of physical models.

This begs the question, when is it most appropriate to use 3-D printed models during scientific modeling. Participants brought up good points about the possible pitfalls of 3-D printed models. One of those was the fact that 3-D printing models typically involved one inflexible material. On the other hand, physical models built by hand usually involve various materials, which arguably may provide explanatory assistance for the student as well as provide knowledge of different materials' properties. Another student mentioned the difficulty they had forming columns that were just the right size to fit in a replica Parthenon. This example illustrates the spatial complexities involved in building physical models by hand. Therefore, a fruitful line of research would be to compare students' development of various types of physical models and their impact on both spatial reasoning and argumentation.

Time constraints levied on this study restricted the amount of time students were able to take part in design based modeling activities. Also, with a case study format I was able to gather in-depth and rich description of the happenings in a design-based modeling intervention, but I was not able to generalize these findings. The spatial increases of the students in this study were promising and the spatial challenges that students encountered were ones that have been found to build spatial abilities in previous research (Martin-Dorta, Saorin, & Contero, 2008). I believe a quasi-experimental study that looks at spatial gains over a longer time period with more participants is needed to add more credibility to the increases in spatial abilities found in this study.

Research using 3-D printing technologies in K-12 educational environments is just emerging. There are several studies that employ Google Sketchup as cad software in order to both integrate engineering into science and to build spatial abilities of students

take her cat is a relatively new browser-based program that is very similar to Google Sketchup but involves mostly three-dimensional building blocks. In the research I've seen using Google Sketchup, students are using the program for an extended amount of time. A study that compared the spatial gains of students when using either Google Sketchup or Tinkercad would be an interesting one. It would also be interesting to know the differences in the types of spatial challenges that users of both software programs would encounter. In this study in a short amount of time students were able to complete their physical model using Tinkercad that was relatively complex. I also wonder how the end products would compare from the aforementioned programs.

Although there seems to be several different evaluation tools for scientific argument, I have yet to find an evaluation tool for scientific argument in the context of design-based instruction. Literature involving design-based instruction often speaks of the benefits of scientific discourse during this type of pedagogy, yet exploration into the discourse during design based instruction has seen little attention. It is important that more studies be developed to investigate student discourse during design-based instruction, like design based modeling. Perhaps this will lead us to an appropriate evaluation tool for scientific argumentation in such a context.

An interesting finding in this study dealt with how sense of ownership impacted argumentation. I was very interested was the fact that although the sense of belonging seem to keep students engaged and interested, it also made them more susceptible to two negative emotions during model critiques. I think it would be very interesting for a study to focus on small group dynamics during a lesson where students generated their own models. It would be interesting to find out how students negotiated the emotions

intertwined within sense of ownership and a classmate's critique of their model. In this study the participant whose feelings were hurt by a critique, still felt that his model was one of the best. This was after each and every participant involved in the study provided him with a somewhat harsh critique. And this was an interesting finding because his model was noticeably of lower quality than most. Does this sense of ownership cloud a student's ability to self-evaluate?

It would also be interesting to know how teachers felt about using 3-D printing technologies in the context of their classroom. I wonder how teachers' perceptions of 3-D printing technologies might change after using 3-D printing technologies in a classroom situation.

In conclusion, due to the emerging areas of research in 3-D printing as an educational tool and as design based instruction as an effective pedagogy, there are many avenues for new research. It is important to understand how CAD software can best be used to build spatial abilities in school-age children. With the small amount of research involving 3-D printing technologies and education and the growing amount of practitioner articles utilizing 3-D printing out technologies and education it is important that much more research on 3-D printer printing technologies is completed. As I visit schools in my local area more and more 3-D printers seem to be creeping into the schools, yet there is little research for either teacher educators or teachers to draw from in order to use the technology most effectively. Argument in the context of design-based instruction is another area of research that needs more attention. This study provided insight into each of these areas, but they all need more attention.

Limitations

This section presents limitations in the study design, context, and the analysis of findings. Although the design of the study dealt with multiple cases on the premise of replication logic, it is apparent that each case was unique. All cases could have been considered high-functioning when it came to spatial abilities, but still there was quite a bit of variance in their pretest scores. This variance meant that the intervention could have impacted their spatial abilities differently. Due to a possible ceiling effect as shown in the analysis of spatial abilities tests, it was difficult to infer true spatial gains by spatial experts. Spatial abilities in general seemed to increase quite a bit in this study compared to other studies mentioned in the paper especially in such a small amount of time. We make no claims on why these intense gains have occurred, but it must be mentioned that this particular group of students were used to competing with each other. They also were all very interested in STEM subjects and activities and were constantly being asked about their work with the 3D printer by other teachers and administrators in the school. Thus, the dynamic of this context could have impacted the engagement and any related gains in spatial abilities of students and may have done the same with other interventions.

During interviews when researchers asked participants to compare their work with others, their context was very limited. In fact, participants only compared their work with those in the top of the class. It was interesting that all students felt that their models were as good or better than others in the group, but I wonder if there answers would have been different if they were comparing their work to the general population. A confounding factor of the interviews was also the polite nature of the students. It was evident at times that students did not speak their mind when discussing their relationship with other

students. Even after second and third follow-up questions, participants were guarded against expressing how they felt about other's feelings. This limitation may have also had to do with the fact that the researcher was an active participant in the study that had an authoritative role. In fact, the researcher spoke about how to argue scientifically without personally offending others. This may have made it difficult for participants to speak truthfully about others' work. This was especially true in Billy and Logan's case. Both had difficulty speaking about each other's models even though it was evident there was great tension between the two. This personal tension that stemmed from issues with working together, may have also had an impact on how they perceived the other's model. Overall though, these students were used to working with and against each other and there were little social issues. I do not believe that the social tension in the group was any more than other educational research set in a normal classroom setting with students working in groups.

It is important to note that the 3D printed models were not always precise in their portrayal of the CAD drawing. Thus, many of the comments that students made dealt with these inaccuracies. That meant that students had to backtrack and try to explain that the way the 3D printed model turned out was not the way they designed it. This may have encouraged more discussion about design process and technical aspects of modeling than would have happened if there were no inaccuracies in the print. However, we felt that this discussion was valuable in that it allowed students to learn the limits of the technology and how design may be limited due to the constraints of the technology available.

At several times during the intervention there were scheduled times for argument across cases for models. These arguments were meant to be student-centered. During the

first scheduled argument in particular, the teacher of the class interrupted the argument to discuss what he believed was the function of the form in question. This happened two separate times during the argument and notably changed the feel of the discussion. The goal of the particular argument in question was to have students establish that they needed more information about the adaptations in order to make conclusions. I spoke to the teacher after this incident and this type of interruption did not happen again. It was evident that students were used to the teacher providing answers to questions and this interruption seemed to only change the discussion of the first argument, but it may have impacted the way students argued throughout- thinking that they should not present ideas that might be “wrong.”

Overall, limitations in this study were what could be expected in educational research involving a specific sample of the population. I believe that these limitations do not impact the trustworthiness of the findings or conclusions of the study.

Summary of Chapter

This study sought to investigate the impact of design based modeling on the spatial abilities and argumentation of seventh grade students. The findings of this study bring many implications covering a broad expanse of science education. This chapter first discussed the theoretical implications of this study. These implications involved the addition of justifications and refutations based on design constraints for scientific argumentation in the context of a design-based modeling. The discussion then moved to the implications this study had on technology in education. 3D printing technologies were mentioned as a viable use for teachers at nearly all age levels. This chapter then presented implications for teacher educators that included the need to expose to preservice and

inservice teachers to theory that explicates the importance of spatial experiences for children and also to provide them tools to help provide impactful experiences. For practicing teachers, many implications were discussed. The importance of allowing students to build 3D models was one of these implications. Future research in the areas of spatial abilities, educational technology, modeling, and argumentation was discussed.

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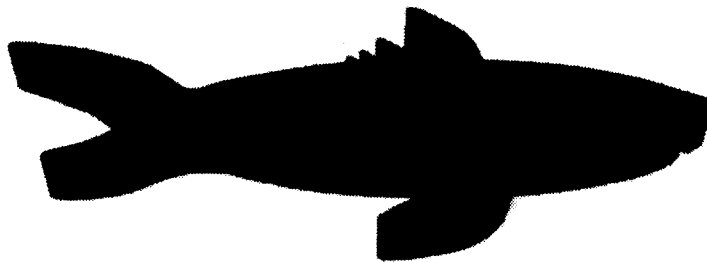
Appendix A

Challenge Guide

Challenge!

The fish model below is living today in the following environment:

- Clear shallow waters with nearby reef
- Quick prey that normally travel just above the ocean floor.
- Quick predators that attack from behind



Fast forward 500,000 years and the environment has gradually changed. The fish lives in an environment with the following characteristics:

- Murky water with minimal light and no reef
- Slow, armored prey living just beneath the sand on the ocean floor.
- Slow predators that attack from above.

Your Challenge is to design a model that represents how the fish has changed in 500,000 years. Also, you will need to explain exactly how and why it changed using your knowledge of natural selection. Below are your tasks for the next few days:

1. Each person brainstorms ideas and draws a sketch (paper and pencil) of the modified model.
2. Complete simulation and match conclusions with your drawing.
3. Each group discusses the best parts of each model and completes a 2nd drawing and fills in chart.
4. Wednesday groups finish design on TinkerCad and have explanations for any changes. Write explanations on the chart.

What changed?	Selection Pressure?	How exactly did it change?

Appendix B

Semi-structured Interview Protocol

(Pre-intervention) Purpose for questionnaire and questions 1-4: RQ1 spatial abilities of students.

1. (Inquiry about questionnaire) Which one of those activities is your favorite?
 - a. Why is it your favorite?
 - b. Are you better at it than all your friends?
 - c. What exactly makes you good at this?
2. Do you play video games?
 - a. What are your favorites?
 - b. Are you better than your friends at this game?
 - c. Why do you say this?
 - d. What kinds of things do you have to do in that game to win.
3. How confident are you in your ability to design a 3 dimensional figure like this (Show them the 3D printed fish model) on the computer?

Highly confident / confident / unsure / not confident / I won't be able to do it

Explain why you feel this way.

4. The fish I just showed you was made on a 3D printer. If you were to make something on a 3D printer, would yours be better/ about the same / or worse than your friends.

Purpose for 5-7: RQ 2 –argumentation and models

5. Have you ever created drawings in science class? Tell me about this.

- a. Have you created them to use for scientific argument (Having to justify your position to others--that may not agree with your initial claim--using scientific evidence)?
 - b. Did creating the drawings help you understand more complex ideas like where things were exactly, how big things were, or how things fit together? Can you explain or give an example?
 - c. Did your drawings become more complex as you were able to complete more?
6. Have you ever created physical models in science class? Tell me about this.
- a. Have you created them to use for scientific argument?
 - i. Are they better than drawings for this?
 - b. Did creating the physical models help you understand more complex ideas like where things were exactly, how big things were, or how things fit together? Can you explain or give an example?
 - i. Did physical models help you understand these things more than drawings?
 - c. Did your physical models become more complex as you were able to complete more of them?
7. Have you ever created 3D printed physical models in science class? Tell me about this.
- a. Have you created them to use for scientific argument?
 - i. Are they better than drawings or other physical models for this?
 - b. Did creating the 3D printed physical models help you understand more complex ideas like where things were exactly, how big things were, or how things fit together? Can you explain or give an example?
 - i. Did 3D printed physical models help you understand these things more than drawings or other physical models?
 - c. Did your 3D printed physical models become more complex as you were able to complete more of them?

Semi-structured Interview Protocol (Post-intervention)

1. The tests you just took are tests of spatial abilities. Compared to others your age, how would you rate your spatial abilities?
 - a. What makes you feel this way?

2. How confident are you in your ability to design a 3 dimensional figure like this (Show them a 3D fish model) on the computer?

Highly confident / confident / unsure / not confident / I won't be able to do it

- a. Has your confidence changed since the beginning of the lesson?
 - b. If so, in what ways?
 - c. For what reasons did your confidence change?
3. How do you think your finished design compared to others' designs in the class?
4. How do you feel about designing models in science class?
 - a. Do you think it helped you learn science?
5. Do you think that the paper and pencil model you created helped you explain science concepts better than you would have without a model?
 - a. If yes, in what ways?
6. Do you think that the 3D printed model you created helped you explain science concepts better than without a model?
 - a. If yes, in what ways?
 - b. Did it help you more or less than the pencil and paper model?
 - c. Can you explain further?
7. Overall, what did you think about this experience?

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McConnell, W. & Dickerson, D. (Under Review). The Impact of 3D Printing Technologies on Students' Participation in a Life Science Lesson. *International Journal of Science Education*.

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SELECTED RESEARCH PAPERS PRESENTED AT PROFESSIONAL MEETINGS

McConnell, W. & Dickerson, D. (April, 2015). *3D printing technology as an educational tool for seventh grade students: Do affordances outweigh constraints?* Presented at the National Association of Research in Science Teaching (NARST) annual conference in Chicago, IL.

McConnell, W. & Butler, B. (April, 2015). *Confronting struggle as a doctoral student: Lessons from a critical friendship with a teacher educator*. Presented at the Annual Conference of the American Educational Research Association (AERA). Chicago, IL.

Butler, B. M., Burgin, S., & **McConnell, W.** (2015, February). *Co-teaching in elementary science and social studies methods: Lessons learned from a socio-scientific issues unit*. Presented at the annual meeting of the Association of Teacher Educators (ATE). Phoenix, AZ.

Butler, B. M., & **McConnell, W.** (2015, February). *Critical friendship in a doctoral seminar: Benefits from the faculty and student perspective*. Presented at the annual meeting of the Association of Teacher Educators (ATE). Phoenix, AZ.

McConnell, W. & Dickerson, D. (January, 2015). *3D Printing and Evolution: Presenting the Future*. Presented at the 22nd annual International Conference of the Association for Science Teacher Education (ASTE). Portland, Oregon.

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